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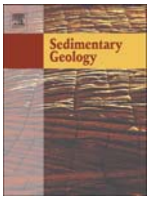

Supercritical flows and their control on the architecture and facies of small-radius sand-rich fan lobes

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ABSTRACT

New insights into flow characteristics of supercritical, high-density turbidity currents initiated renewed interest in a sand-rich lobe complex near the hamlet of Mizala in the Sorbas Basin (Tortonian, SE Spain). The field study was done using drone-made images taken along bed strike in combination with physical tracing of bounding surfaces and section logging. The studied lobe systems show a consistent built-up of lobe elements of 1.5–2.0 m thick, which form the building 'blocks' of the lobe system. The stacking of lobe elements shows lateral shift and compensational relief infill. The new model outlined in this paper highlights three stages of fan lobe development: I. an early aggradational stage with lobe elements characterized by antidune and traction-carpet bedforms and burrowed mud intervals (here called 'distal fan' deposits); II. a progradational stage, where the distal fan deposits are truncated by lobe elements of amalgamated sandy to gravelly units characterized by cyclic step bedform facies (designated as 'supra fan' deposits). The supra fan is much more channelized and scoured and of higher flow energy than the distal-fan. Aggradation of the supra-fan is terminated by a 'pappy' pebbly sandstone and by substrate liquefaction, 'pappy' referring to a typical, porridge-like texture indicating rapid deposition under conditions of little-to-no shear. The facies-bounded termination of the supra-fan is here related to its maximum elevation, causing the lobe-feeding supercritical flow to choke and to expand upwards by a strong hydraulic jump at the channel outlet; III. a backfilling stage, characterized by backfilling of the remaining relief with progressively thinning and fining of turbidite beds and eventually with mud. The three-stage development for fan-lobe building is deducted from reoccurring architectural and facies characteristics in three successive fan-lobes. The validity of using experimental, supercritical-flow fan studies for understanding the intrinsic mechanisms in sand-rich-fan lobe development is discussed.

1. Introduction

In tectonic active areas and in intermontane basins, coarse-grained and small-radius (<10 km) submarine fans develop on relatively steep slopes. Fans in such configurations have been sparsely studied from modern (e.g., Normark, 1970; Gervais et al., 2004, 2006; Deptuck et al., 2008) and ancient record (e.g., Cazzola et al., 1981, 1984, 1985; Walker, 1978; Mutti and Normark, 1987; Kleverlaan, 1989; Reading, 1996). Small radius fans are sand-rich with a high Net to Gross ratio (>70), which make them prolific petroleum reservoirs, whose architecture and facies are of interest to the petroleum industry.

Only a few studies are available that focus on the morphodynamics of these fans. Available case studies generally agree that the turbidity currents shaping these fans have low transport efficiency and deposit massive sands that aggrade to form an elevated middle- or supra fan based on studies of the modern Lajolla and San Lucas fans (Californian deep sea basins; Normark, 1970) and Golo fan (Corsican trough, Italy; Gervais et al., 2004, 2006; Deptuck et al., 2008). Outcrop examples include the Eocene Rocks Sandstones in California (Link and Nilsen, 1980), the late Miocene Tabernas fan complex in southeast Spain (Kleverlaan, 1989), the late Oligocene to early Miocene Cengio Turbidite complex in NW Italy (Cazzola et al., 1981, 1984, 1985; Felletti and Bersezio, 2010), and the Eocene deep-water fan deltas of the Vilomare section of the Llorenç del Munt in N Spain (López-Blanco et al., 2000a, 2000b; Postma et al., 2016). All these fan systems are interpreted as being fed mainly by river floods and minor slope-instability events. Their fan lobes show the following characteristics: (1) they are located at the termination of the upper-fan valley; (2) they exhibit an overall convex-upward relief in radial profile; (3) they contain coarse-grained turbidites (predominantly sands); (4) their inner portions are channeled and outer portions are unchanneled; (5) they show braided channels; and (6) slumps are common (Walker, 1978). The fan lobes of the modern Golo fan on the west flank of the Corsican Trough are well studied modern examples of small radius fans with elevated middle fan segments (Gervais et al., 2006; Deptuck et al., 2008).

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The upper-fan valley slope of small radius fans is sufficiently steep to make turbidity currents supercritical. The fan lobes in the Corsican trough are on slopes of 0.5–3.0° (Gervais et al., 2004, 2006; Deptuck et al., 2008), which is more than sufficient for turbidity currents to be supercritical. Sequeiros (2012) finds minimum slopes of 0.01 for density flow supercriticality, thus on slopes as low as ~0.5°. The similar-sized Tortonian submarine fans of the Tabernas Basin (southeast Spain; Kleverlaan, 1989) show abundant bedforms including cyclic steps that demonstrate flow supercriticality (Postma et al., 2014).

The morphodynamics of submarine fans fed by supercritical density flows have been studied experimentally in the Exxon Research laboratories by Hoyal and Sheets (2009). In their experiments, supercritical ($Fr' > 1$) saline density flows eroded a 'bypass channel' that eventually shallowed into an aggrading fan lobe. The lateral migration of the channel forced sideward stepping of the lobe during a period of predominantly sheet flow. Further aggradation progressively slowed down the channel extension and eventually choked the supercritical flow forcing it through a hydraulic jump, which heralded the backfill of the channel that finally leads to avulsion and the creation of a new channel. The experiments of Hoyal and Sheets (2009) and the similar and more recent experiments of Hamilton et al. (2015, 2017) show that intrinsic system mechanics are somehow related to the channel hydraulics and flow characteristics in the channel on the one hand and maximal lobe elevation that the flow can pass on the other.

The aim of this study is to gain additional insight into the morphodynamics of small radius, sand-rich fans. Important questions examined in this study include how do turbidite events build the fan lobes, and what is the interaction between the feeding turbidity current and the lobe it is creating? To keep mapping and architectural studies manageable, we chose small-scale lobe complexes NW of the hamlet Mizala located in the southern part of the Sorbas Basin (SE Spain, Fig. 1) to answer these questions. Guiding objectives were 1) reconstruction of flow characteristics through bedform analysis; 2) establishment of detailed fan-lobe stratigraphy and facies associations; 3) detailed mapping of the extension of facies associations (fan lobe elements); 4) establishment of a generic fan-lobe depositional model; and 5) comparing field-inferred morphodynamics with existing experimental studies of fan lobe development to address the impact of flow characteristics on lobe features.

2. Geological setting of the turbidite successions

The Sorbas Basin in southeast Spain is surrounded by metamorphic domes with mainly low-grade metamorphic rocks in the Alpujarride Complex outcropping in the south and high-grade metamorphic rocks of the Nevado-Filabride Complex in the north (Vissers et al., 1995; Martínez-Martínez and Azañón, 1997). The southern dome, the present Sierra Alhamilla was a submarine high in Tortonian times, not delivering detritus (Weijermars et al., 1985). The high grade metamorphics in the northern dome were the main source for detritus in the here described fans, since clast composition of the studied turbidites consists of schists, gneiss, black and grey dolomite, quartzite, and mica schists. Provenance is further confirmed by the south-easterly paleo-flow direction (Fig. 1).

Gravity modelling in the Sorbas Basin revealed a 1.5–2.5 km deep, asymmetric half-graben structure with the hanging wall dipping south and with a normal- to normal-strike-slip fault trending E-W (Do Couto et al., 2014). The gravity sections reveal that the southern part of the Sorbas basin acted as an active depocenter, with the basin floor locally at a depth that varied between 1 and 2 km. The measured distance from the paleo-shoreline must have been about 15–20 km, which means that the averaged slope is around 3° or 0.05.

The southern folded boundary of the Sorbas Basin displays a continuous growth-strata structure forming a recumbent syncline. About 10 km west of Mizala, fault-slip data inversion indicates a N-S maximum compression. It led to a rather thick accumulation (up to about 1000 m according to Ott d'Estevou and Montenat, 1990) of upper Tortonian marine turbiditic sediments along the southern margin of the Sorbas Basin that is studied here (see also Weijermars et al., 1985; Ott d'Estevou and Montenat, 1990; Johnson et al., 1997; Vázquez et al., 2011; Do Couto et al., 2014). Progressive unconformities (e.g., growth-strata) in upper Tortonian sediments (8.00–7.24 Ma) mark the growth of the Sierra Alhamilla basement range during a compressional episode. It shaped most of the current geologic and topographic features of the southeastern parts of the Internal Zones of the Betic Cordillera, tilted the turbidite sequences (Do Couto et al., 2014) and produced a NW-SE trending fault system that offsets the turbidite sequences up to several meters in the study area (Fig. 1D).

The overlying Messinian carbonates and evaporates seal most of the folding linked with the growth of the Sierra Alhamilla range (Weijermars et al., 1985; Ott d'Estevou and Montenat, 1990), but are in turn involved in the present-day, large-scale open-fold of the Sorbas basin.

3. Methodology

Architecture and bed continuity in the study area was mapped by physical tracing in the field with help of 3-dimensional image compositions (Agisoft photo scan software). The images (14 megapixel resolution) were made by Phantom Vision 2 + drone-attached camera with GPS positioning system. The quality of the 3D compositions was sufficient for mapping purposes but too crude for architectural and facies studies. For the purpose of our architectural studies, great effort was put in making drone images precisely in the strike direction to avoid apparent dips due to outcrop morphology. These images were later corrected for fish-eye lens-deformation in Adobe Photoshop. The surveyed area (~1 km^2) was geologically mapped (Fig. 1D) and detailed sedimentary logs were taken from the best outcrops in this area as shown in Fig. 2.

The fan lobe terminology developed by Mulder and Etienne (2010) and Gaillot et al. (2015) is followed here: A fan lobe complex consists of fan lobe systems generally enveloped in mud as seen in Fig. 2. Each fan-lobe system is built up by lobe elements and each lobe element contains several beds.

Turbidite facies are described by using the newly proposed facies schemes of Talling et al. (2012) and Postma and Cartigny (2014) for sub- and super-critical turbidity current deposits (Fig. 3). The Bouma sequence (Bouma, 1962) with five different facies abbreviated as Ta-Te units is used as overall facies framework. In the facies scheme, the Tb unit has been expanded for high concentration flow deposits to include facies that have been related to the sediment concentration of the basal flow layer of high-density stratified flows (Cartigny et al., 2013; Postma et al., 2014). The left column in Fig. 1 represents facies associated with flow over cyclic steps. Deposition on the stoss side of cyclic steps is controlled first by strongly decelerating flow in the hydraulic jump zone and then by waxing flow (Postma et al., 2014). Facies at the hydraulic jump is characterized by soft-sediment deformation (flame structures), by substrate liquefaction and by structureless coarse-tail normally graded sediments deposited during conditions of hindered settling with virtually no horizontal shear (see Postma et al., 2009, 2014). Downslope and away from the hydraulic jump flow shear along the bed increases and depositional facies become increasingly more stratified from almost structureless (Tb4), via crude (Tb3b) and spaced stratification (Tb3a) to planar laminations with spacing smaller than 0.5 cm (Tb2) near the crest (Postma et al., 2014) (Fig. 3). Tb1 represents the plane bed facies of Bouma formerly denoted by Tb.

4. Description of the Mizala fans

Three out of at least 7 fan lobes have been studied in detail and are delineated by blue, orange and green lines in Fig. 2. The three lobe sequences vary in thickness ranging from about 10 to 17.5 m and all