Chapter 47
Morphodynamics of Supercritical Turbidity Currents in the Channel-Lobe Transition Zone

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Abstract This study aims to resolve process-facies links at both bed and environmental scales for the channel lobe transition zone (CLTZ). Data comes from existing experimental and modern CLTZ studies and from new outcrop studies. The experiments show that the CLTZ architecture of supercritical turbidity currents is complex and different from their counterparts where flows are subcritical throughout. Supercritical CLTZ's are characterised by erosive channels formed by supercritical turbidity currents, by offset stacked lobes deposited from subcritical turbidity currents and by hydraulic jump related mouth bar deposits and upslope onlapping backfill deposits at the down slope end of the transition zone. Erosive channels and backfill features can be resolved by high resolution seismic data, yet evidence for supercritical flow must come from facies analysis of core data. Outcrop examples of the CLTZ from the Tabernas submarine fan (SE Spain) and the Llorenç del Munt deep-water delta slope (N. Spain) are used to establish such links between seismic scale architecture and facies recognised in cores. The outcrops described here were mapped as transition zone, and show 100 m sized, spoon-shaped scours filled with sediment containing sandy to gravelly backsets up to 4 m in height. Their facies and architecture is indicative of deposition by hydraulic jumps, can be recognized from cores, and is a good proxy for further predicting CLTZ architecture constructed by supercritical turbidity currents.

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47.1 Introduction

The morphodynamics of turbidity currents at the transition from confined channels to unconfined lobes, commonly referred to as the channel-lobe transition zone (CLTZ), is still a poorly explored part of the submarine turbidite fan environment. Consequently, making inferences about sand body architecture and facies in cored CLTZ successions remains uncertain.

Features of the CLTZ recognized from the modern seafloor vary. Turbidite deposits are commonly patchily distributed and extensively reworked (Wynn et al. 2002). Lobes can have complex architecture with numerous onlap, toplap and downlap surfaces built by numerous events (Gervais et al. 2006). Both seismic and sea floor data reveal that lobes may contain many small channels indicating that gravity flows remain confined at least for their basal part across most of the lobe for some of the turbidite events (Gervais et al. 2006). Under sediment bypass conditions, the CLTZ is characterized by abundant erosional features, including isolated spoon- and chevron-shaped scours up to 20 m deep, 2 km wide, and 2.5 km long, partially filled with coarse-grained material that is trapped in the scour (e.g. MacDonald et al. 2011a, their Table 1). The CLTZ of the Monterey Canyon exhibits elongated sand fingers and shallow channels filled with sand (Klaucke et al. 2004). In contrast, CLTZ's on the slope east of Corsica (Gervais et al. 2004) are characterised by (1) small proximal isolated lobes (PILs) connected with local slope gullies and deposited at the slope break ($3^\circ \rightarrow 1.5^\circ$), and (2) somewhat larger composite midfan lobes (CMLs) on slopes of 1.5–1° that are connected with erosive and leveed channels issuing from large canyons. The CMLs were probably river fed during sea-level low stands and have more complex architecture than the PILs (see further Deptuck et al. 2008).

Sediment bypass features of inferred CLTZ similar to those described by Wynn et al. (2002) and Deptuck et al. (2008) have occasionally been inferred from ancient turbidite successions. In particular the bypass zones in the turbidite series of the Hecho Basin (Pyrenees, see Mutti and Normark 1987) and the Ross Formation (Ireland, see Chapin et al. 1994; Macdonald et al. 2011b), the latter displaying chevron shaped scours (Elliott 2000) are well known.

It is hypothesized in this paper that some of the CLTZ depositional complexities can be significantly clarified by considering the flow domain of turbidity currents. Recent experimental fan and field studies suggest that sub- and supercritical turbidity currents each have a characteristic architecture (Cantelli et al. 2011; Fernandez et al. 2014; Hoyal and Sheets 2009; Hamilton et al. 2015) and facies associations (Postma and Cartigny 2014). The objectives of our CLTZ studies include highlighting the relevance of the critical densimetric Froude number for facies and architectural development in the CLTZ.

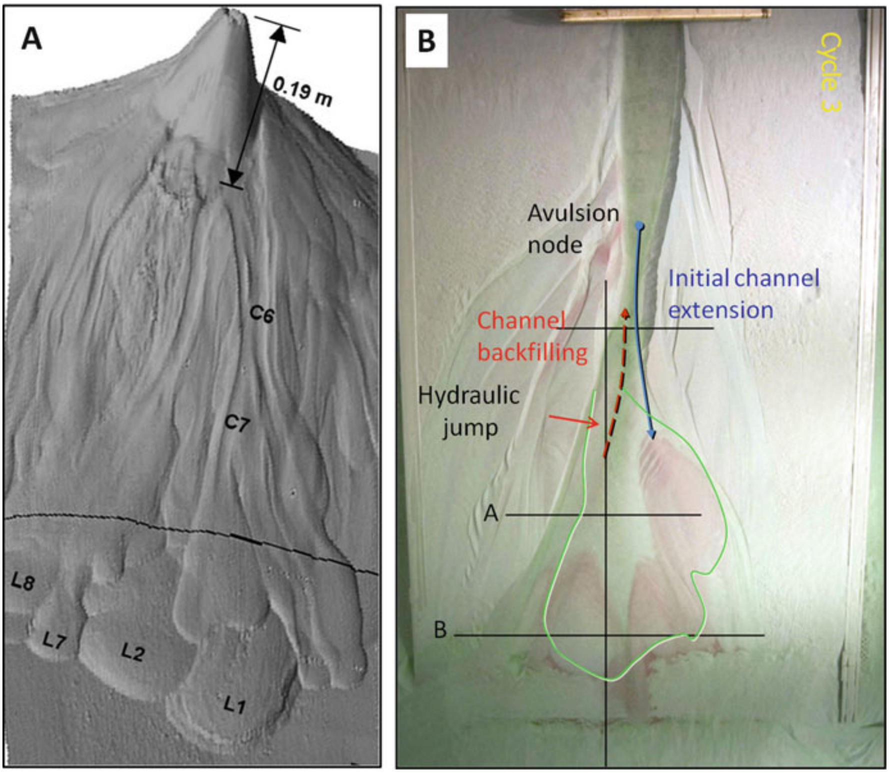

Fig. 47.1 Experimental studies of channel lobe systems. Table length in both **a** and **b** is 3 m: (**a**) Subcritical channel lobe system of Fernandez et al. (2014) with 5–45 μm silica particle slurries of 5–10 % volume concentration over 4° slope. The 0.19 measure is the height drop onto the slope; (**b**) supercritical channel lobe system of Hoyal and Sheets (2009) and Hamilton et al. (2015) with saline underflow over 10° slope and transporting 180–250 μm crushed plastic particles over a similar substrate. Cross-sections **a** and **b** are given in Fig. 47.5a, b

47.2 Experimental Analogues of Channelized Submarine Fans

Experiments with *subcritical* kaolinite suspensions showed numerous channels formed by levee building, which avulsed near the steep cone as the fan evolved (Fig. 47.1a, Cantelli et al. 2011; Fernandez et al. 2014). Lobes formed once the channels crossed the break of slope, and channel-lobe tracts were typically maintained over several flows. Compensational deposition occurred at a time scale that was longer than that of the individual runs (Fernandez et al. 2014). The resulting architecture was mainly aggradational with channel levee elements above and lobes below the slope break.

In experiments with *supercritical* saline density flows, channels were not formed by levee building, but through erosion, thus forming a ‘bypass channel’ (Hoyal and Sheets 2009; Hamilton et al. 2015). Eventually, an extending channel stagnates and aggrades a mouth bar ahead of itself thus creating an obstacle, which progressively slows down the supercritical flow to subcritical through a hydraulic jump. Backsets develop in the scour just upstream of the mouth bar, backfilling the channel. It is interesting to note that channel stagnation occurred in the experiments on the sloping portion of the domain, i.e., a slope break did not play a role in restraining the system as it did in the subcritical case. Eventually, the backfill of the channel leads to avulsion and the creation of a new channel (Fig. 47.1b).

The conditions for forcing a hydraulic jump on a slope depends on the flow's densimetric Froude number and thus on its density and velocity, which is a function of slope. If the slope is mild then a downstream subcritical normal flow boundary condition is likely to force the jump. If the slope is steep, then it is likely that the jump is forced by a stepped obstruction (see Hamilton et al. 2015). Flow density plays a role in the required height of the obstruction: dilute flows with high velocities require a very large stepped obstruction, many times the flow thickness, to trigger a jump, while dense flows with relatively low velocities require very small steps (Hamilton et al. 2015).

47.3 Facies Associations

The difference in morphodynamics of the sub- and supercritical CLTZ experiments is striking. The subcritical CLTZ is mainly progradational and aggradational, forming tabular, compensationally stacked channels and lobes, while the supercritical CLTZ shows bypass zones characterized by erosion and hydraulic jump related deposits. The stacking of channel and lobes in the supercritical case is complex showing channel erosion, offset stacked lobes and backfilling patterns including hydraulic jump deposits. Each cycle (see Fig. 47.1b) starts with avulsion and channel elongation, followed by onlap (mouth bar), flow stagnation (hydraulic jump deposits) and bypass features and ends with channel abandonment (mud cover). Hydraulic jump related deposits can be easily recognised by their backset architecture filling an asymmetrical scour. Facies associations related to a hydraulic jump is typically Ta, Tb4 – Tb3a (see Fig. 47.2, Postma and Cartigny 2014; Russell and Arnott 2003) indicating high concentration and little shear of the flow during deposition. Ta facies is often in combination with soft sediment deformation structures in particular flames at the base of the bed (Postma et al. 2009) and angular mud chips ripped up locally from the substrate (Postma et al. 2014).

47.4 Field Observations

Superb examples of supercritical CLTZ turbidites have been found in the late Miocene submarine fan deposits of the Tabernas basin, mapped by Kleverlaan (1989a). The inferred transition zone stretches over several kilometres from the

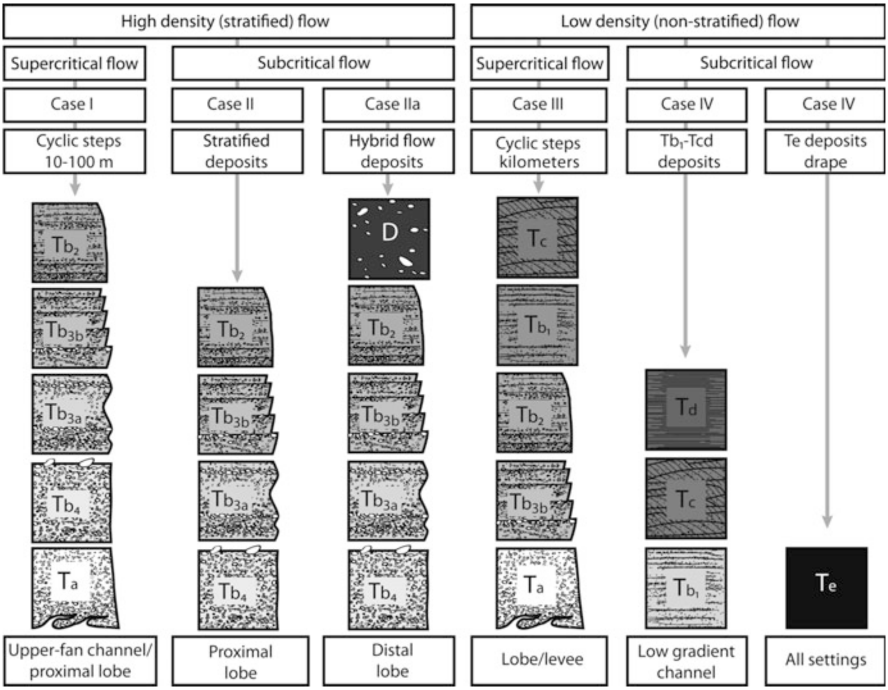

Fig. 47.2 Facies associations for the channel lobe transition zone, which can be read from cores (From Postma and Cartigny 2014). T unit legend: Ta = coarse-tail normally graded with flame structures at the base; Tb4 = mainly massive and inversely graded; Tb3a = crude stratification; Tb3b = spaced stratification; Tb2 = <0.5 cm planar stratification; Tb1 = plane bed lamination with parting lineation; Tc = ripples; Td = plane bed of the lower flow regime and Te = hemipelagic fall out; D = debrite

canyon ('Buho Canyon') to the lobe deposits (Kleverlaan 1989b). Its facies is characterized by large, asymmetric gravel lenses enveloped in bioturbated mud (Fig. 47.3). The gravel units are characterized by upcurrent dipping crude stratification (Tb4 and Tb3a) and structureless gravel nests (Ta). This up-flow dipping crude stratification forms backset beds. They are seen locally to grade upslope into a structureless gravel, with vertical clast fabrics. Imbricated clasts dip slightly steeper than the upslope dipping cross stratifications pointing to flow traction, hence distinguishing the deposit from a debris flow origin. The top of the gravel units is sharp (grain size change from gravel to mud) and wavy possibly pointing to a bypassing supercritical flow. Clusters of outsized clasts drape the wavy surface that is overlain by bioturbated, thin sand and mud layers.

Sedimentation units in the transition zone comprise stacks of up to several meters thickness of the above described gravel lenses, and alternating dm's thick sandy (Tb4-2) and homogenised muddy turbidite beds. The stacking has an aggradational (little vertical change in bedding and grain size) to progradational (overall coarsening) character. The lobe consist of turbidite sheets with rare Ta facies, some Tb4-1 and abundant Tcde (see Cartigny 2012).

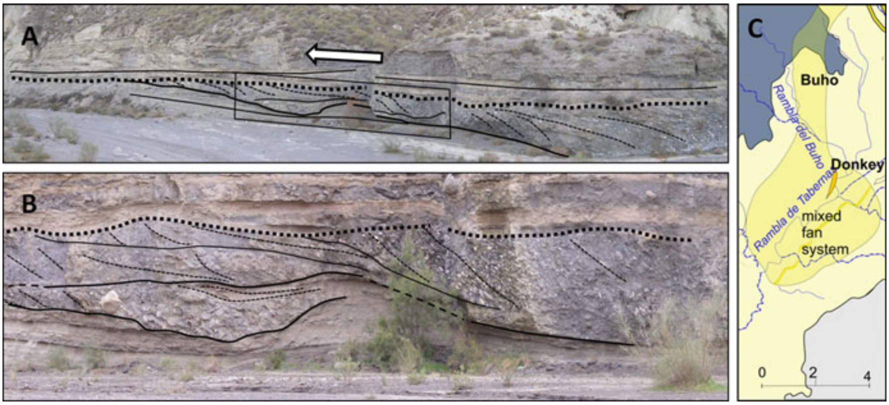

Fig. 47.3 Supercritical CLTZ bypass zone of the mixed sand-mud turbidite fan (Tabernas Basin); (**a**) Amalgamated spoon-shaped scours filled with cross stratified gravel (backsets); Paleo-flow is from right to the left and obliquely into the outcrop. Outcrop width on picture is about 200 m; (**b**) Detail of **a** showing large, trough-shaped sets of gravelly backsets with well defined wavy erosive surface at the top of the bed; Note the multiple event infill of the scour by variously stacked backsets, and chaotic massive fill at the base. Outcrop height is about 5.5 m, (**c**) Map of the area North of the village Tabernas showing main features of mapped CLTZ time slice in *yellow* (see Kleverlaan 1989a, b for details). South is to the left

Another example comes from the deep-water fan deltas of the Vilomara section of Llorenç del Munt fan delta complex, mapped and studied for its sequence stratigraphy by López Blanco et al. (2000a, b, Fig. 47.4). At the base of the Vilomara section, sandy turbidite beds are seen onlapping an erosive surface on the muddy slope of the delta. The outcrop has no obvious break in slope (Fig. 47.4). Facies that includes Ta and Tb4-1 are believed to indicate supercritical flow (see Fig. 47.2). These turbidite beds are truncated by a thick sand deposit up to 3 m thick at its centre, which has a large backset and a distinct bypass surface at its top (dotted white line in Fig. 47.4). Note the change in relief (c. 0,80 m) between the upstream section and the backset.

47.5 Discussion and Conclusion

The diagnostic features for supercritical flow controlled CLTZ that emerged from the experimental studies of Hoyal and Sheets (2009) and Hamilton et al. (2015) are (1) extending erosive channels that feed and prograde the lobe and (2) a hydraulic jump that heralds the backfilling of the channel and the development of a mouth bar. The latter process is likely marked by scours filled with steep backset bedding, but also by stacks of more gently upslope dipping and onlapping beds. The proximal isolated lobes (PILs) and the complex midfan lobes (CMLs) of the Golo fan on the lower slope east of Corsica (Gervais et al. 2004; Deptuck et al. 2008) might be a

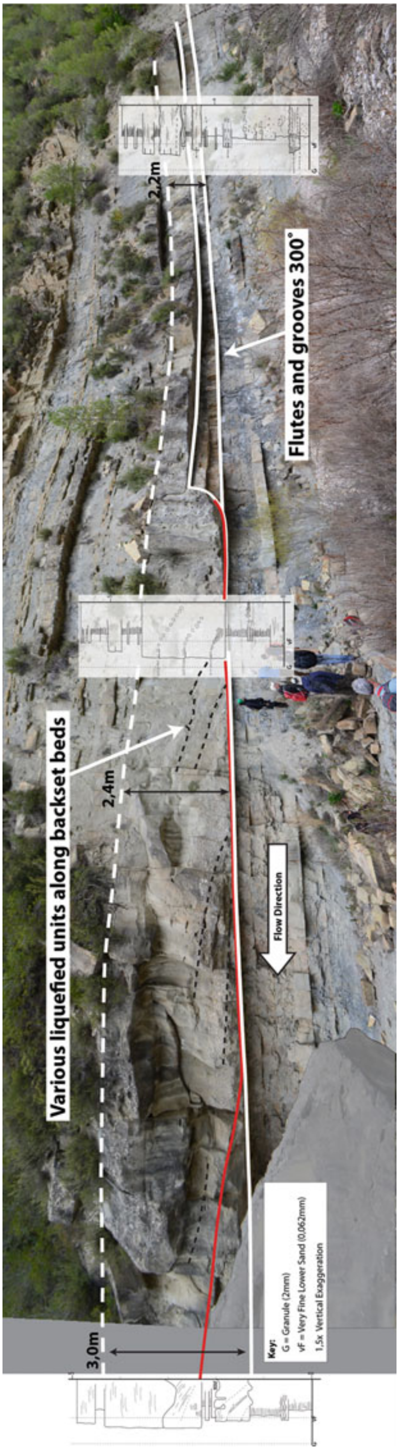

Fig. 47.4 Example of scour filling sediment body on a continuous sloping surface (*white solid line*) of the Llorenç del Munt fan delta (Vilomara section, N. Spain). The internal architecture of the body consists of variously oriented backsets (not clear from photograph), which are interpreted to have formed by hydraulic jumps in successive flow events. Beds within the backsets show abundant soft sediment deformation structures. The *dotted white line* marks a bypass surface with characteristic grain size jump. Detailed logs illustrate the grain size variation which is up to granules (*G*) in the thicker units and down to very fine lower sand (*vF*) in the tabular turbidite beds. South is to the *right*

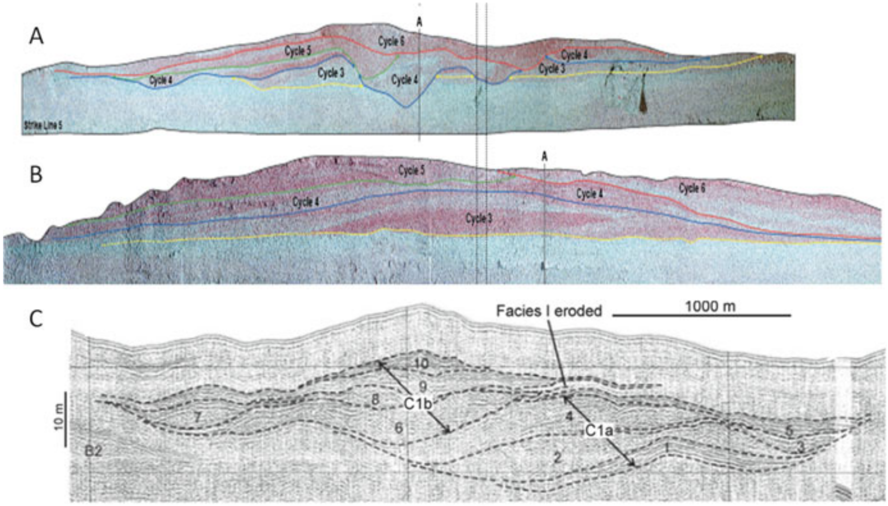

Fig. 47.5 Cross-sections lines *A* and *B* (see Fig. 47.1b) of the supercritical CLTZ experiments (Hoyal and Sheets 2009, with thanks to Roger Bloch). Vertical exaggeration is about 1.8; *C*. Cross-section from the C1 complex midfan lobe (Deptuck et al. 2008)

nice analogue for supercritical CLTZ systems. Both lobe systems are deposited on relatively steep slopes in excess of 1° favouring development of supercritical turbidity currents (Sequeiros 2012). In case of the PILs most abrupt deposition is taking place within a few kilometres of the gully mouth near the slope break. Seismic facies of the proximal parts of the lobe is typical for thick massive and probably amalgamated sand beds onlapping up slope, while cores through the proximal front of the bar show nearly 5 m of continuous massive coarse-grained sands with clay chips probably consisting of a series of amalgamated beds. These lobes may have formed when the outer shelf was inundated during the last transgression and, hence, may have been supplied from inefficient surge like flows triggered when sandy shoals or bars near the heads of gullies failed (see Deptuck et al. 2008). The architecture of CMLs in Golo fan is much more complex and is analogous to the complexity observed in the fans formed in the supercritical flow experiments. Cross sections through these fan lobes have combinations of channel erosion and offset stacking of lobes similar to those observed in experimental studies (Fig. 47.5). Cores and seismic data reveal predominant massive and amalgamated beds in the proximal lobe regions. Sustained mixed-load hyperpycnal flows were most likely to reach the fan during periods of low sea-level stands, but surge-like flows were probably also triggered after a temporary period of storage in the canyon head (Deptuck et al. 2008).

Facies and architecture of the outcrop examples shown by Figs. 47.3 and 47.4 support an interpretation that the sediment bodies were formed in a hydraulic jump zone (see also Russell and Arnott 2003; Postma and Cartigny 2014). Their size, however, is an order of magnitude smaller than the features described from the PILs and CMLs of the east Corsican slope. Hence, these scour fills are not the mouth bar themselves, but rather represent features of the erosive channel floor upslope of the mouth bar in the transition zone similar to the scours found by Wynn et al. (2002), Chapin et al. (1994), and Macdonald et al. (2011b).

In conclusion, by combining experimental studies with studies on small modern fans predictive models emerge for facies and process studies on outcrops in the CLTZ. We infer that the Froude number of turbidity currents is an important parameter to consider when dealing with the CLTZ environments, and perhaps most promising is that this parameter has characteristic facies that can be identified from core.

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