DEPOSITIONAL EVOLUTION OF CONFINED TURBIDITE BASINS

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ABSTRACT: Confined turbidite basins are a common feature of many structurally complex continental slopes, but their depositional history has never been characterized using outcrop data. A synthesis of outcrop data from Tertiary Alpine basins with subsurface data from the Gulf of Mexico indicates that the progressive infill of confined turbidite basins can be characterized by four phases: (1) Flow ponding, where incoming flows are totally trapped, depositing thick, sheet-like sand-mud complexes. (2) Flow stripping, where the finer, more dilute portion of the flow is able to escape over the confining topography to be deposited elsewhere, causing increased sand/mud ratio within the basin. (3) Flow bypass, either by flows traversing over the filled basin or by switching of feeder channels away from the basin; the former resulting in incision, the latter in abandonment. (4) Blanketing, of the basin and surrounding topography due to base-level rise; this usually takes the form of meandering channel-levee complexes with low sand/mud ratios. Confined basin sequences may be stacked during the episodic growth of the confining topography to a basin, and may appear similar to sea-level-induced depositional sequences.

INTRODUCTION

Seismic and well data from the Gulf of Mexico have identified a characteristic stratigraphic history to the numerous salt-withdrawal basins located on the continental slope (Winker 1996; Prather et al. 1998). Initial sediment deposition by turbidity currents onlaps basin margins as it fills local accommodation space perched on the upper slope. Subsequently, as the upper sub-basins become filled, so sediment spills into the next basin located downslope; hence, this stratigraphic development has been termed “fill-and-spill.” This style of sediment dispersal has also been interpreted from the Paleocene of the U.K., Atlantic margin (Lamers and Carmichael 1999), and the Lower Cretaceous of the North Sea (Argent et al. 2000). Outcrop documentation of fill-and-spill processes have been reported from the Eocene-Oligocene Annot Sandstones of southeast France (Sinclair 2000; Tomasso 2001), with evidence of abandonment following filling from the Eocene-Oligocene Taveyannaz Sandstones of eastern Switzerland (Sinclair 1992).

Given the complex topography developed by faulting, diapirism, and mass-wasting on most extensional passive continental slopes, and by thrusting on convergent margins, it is reasonable to expect that confined, intraslope turbidite basins are a common phenomenon; however, the sedimentological history of these basins has not been characterized using outcrop data. This paper aims to provide a depositional model for the progressive filling of confined turbidite basins based on a synthesis of observations and interpretations from previously published data. These publications are based on: (1) present-day and recent processes in the Gulf of Mexico imaged from seismic and side-scan sonar; (2) the stratigraphy and sedimentology of the Annot Sandstones, southeast France, and the Taveyannaz Sandstones, eastern Switzerland; and (3) turbidity-current dynamics in topographically complex settings.

GULF OF MEXICO

Present-day bathymetry of the continental slope of the northern Gulf of Mexico exhibits a complex morphology characterized by 15 to 20 km diameter smooth lows representing perched intraslope basins, separated by salt-induced ridges. Satterfield and Behrens (1990) used shallow, high-resolution seismic to identify meandering channel-levee systems aggrading over filled basins of the upper slope, and which were transformed into incised canyons cutting into the interbasinal, salt-cored highs. A number of geologists working for Shell identified onlapping, well layered units in the upper parts of these basins that were incised by channels that supplied sediment to the next basin downslope (Holman and Robertson 1994; McGee et al. 1994; Winker 1996). These studies represent the first documentation of fill-and-spill depositional processes in confined basins. The concepts of fill and spill were then developed further by Prather et al. (1998), who reviewed a number of basins in the region, and characterized sedimentary facies of these basins including an early, sheet-like, “ponied facies assemblage,” overlay an even more channelized, “bypass facies assemblage.”

The Auger Basin provides detailed information on its fill history (McGee et al. 1994; Prather et al. 1998; Booth and DuVernay 2000); it comprises a lower, 70 m thick, Plio-Pleistocene succession of laterally continuous, onlapping massive sands and muds (the “S” sands) interpreted as ponded turbidite facies. These are overlain by the “R” sands, which comprise layered sheet sands overlain by thinner amalgamated sheet sands and capped by amalgamated, non-levée channel sands. This succession is interpreted as having resulted from the reduction in accommodation space during filling of the basin leading to increased amalgamation and bypass during accumulation of the “R” sands (McGee et al. 1994). A similar succession has been identified from the similar aged “J” sands of the Bullwinkle Basin (Holman and Robertson 1994). Intercalated with these sands are extensive slump and debris-flow horizons. Although seismic mapping indicated that individual sand bodies in the lower “J” sands were laterally continuous, and separated by mud intervals, pressure tests indicated that these beds are all in pressure communication. Interestingly, it has been proposed that cycles of fluctuating accommodation space generated by episodic growth of the confining topography of the Bullwinkle Basin have resulted in repeated ponding to bypass facies assemblages. In yet another of the many basins in this region, Horine et al. (2000) have documented 80 to 200 m thick clean sands that form the S-10 reservoir of the Troika Field. They interpreted these sands as a record of flow stripping of turbidity currents, removing the finer-grained component of the sediment from the basin.

THE ANNOT SANDSTONES

The Eocene-Oligocene Annot Sandstones were deposited onto a complex basin-floor topography in the French Alpine foreland basin (Elliott et al. 1985; Pickering and Hilton 1998; Sinclair 2000). The basin-floor morphology has been reconstructed for the western outcrops of the Annot Sandstones (Fig. 1A; Sinclair 2000) and is composed of a southern sub-basin with a depth of at least 800 m, and a diameter of approximately 20 km. This was separated from a northern sub-basin by a paleo-high that was incised to form an interbasinal canyon (the Coyer Canyon), which was at least 200 m deep and up to 4 km wide. The northern sub-basin was confined to the south by the interbasinal high but was open northwards to the main Alpine foreland basin. These basins were sourced from the south and the east (Stanley 1961, 1980).

The lower succession of the southern sub-basin is composed of a 150 m thick, coarsening- and thickening-upward succession with a 50% mean sandstone/mudstone ratio (Sinclair 2000). Notable features of the individual turbidites include stepwise grading, slumped units, and prevalence of mudstone clasts. The lowestmost 20 m includes thick (2–3 m), structureless mudstones. The middle part of the basin fill is dominated by 400 m of tabular, interbedded, very thick-, to medium-bedded sandstones and mudstones with a sandstone/mudstone ratio ranging from 70 to 95%. Individual turbidites comprise a thick, massive, poorly sorted, coarse-grained sandstone lower unit abruptly overlying and laterally classified into finer-grained sandstones and siltstones, capped by a thin mudstone. Palaeocurrents in this part of the succession are variable, ranging from northwestern to southwestern flow (Kneller and McCaffrey 1999; Sinclair 2000). Overlying this part of the succession are 300 m of tabular, thick-bedded, amalgamated, massive, coarse sandstones with sandstone/mudstone ratios of > 95%. Towards the upper part of this sandstone-rich interval is a major erosion surface that truncates at least 30 m of the underlying succession (Fig. 1A) and is overlain by amalgamated sandstones with extensive truncation of 10 to 15 m at their bases (see Sinclair 2000, figs. 10 and 11).

The infill of the northern sub-basin is at least 2000 m thick, and is more mudstone-rich and thinner-bedded than the southern sub-basin. The dominant facies are medium to thick-bedded, turbiditic sandstones and mudstones. The onlap surface onto the northern slope of the interbasinal high is immediately overlain by 50 to 100 m of brown, thin-bedded, siliciclastic mudstones and siltstones, and underlain by light gray hemipelagic mudstones (Sinclair 1994, fig. 7; Sinclair 2000, fig. 3). Where the infill of the northern sub-basin onlaps the northern margin of the Coyer Canyon, sandstone packages (10–30 m thick) contain much evidence of slumping, dewatering, and amalgamation of sandstone-rich beds. Capping the northern sub-basin is a 20 m condensed interval composed of bioturbated mudstones and hemipelagic marls. At the base of the Coyer Canyon there is a series of steep-sided channels, ranging from 50 to 200 m wide and 20 to 50 m deep, that cut down into the underlying hemipelagic mudstones. Overlying these are a succession of turbiditic sandstones and mudstones that have been interpreted as the deposits of broad shallow channels that fed sheeted sand bodies (Sinclair 2000). Palaeocurrents throughout this succession were towards the north-northwest.
The southern sub-basin is interpreted as a fully confined, intraslope basin with a lower fill recording flow ponding (Apps 1987; Sinclair 2000). The upward increase in the sandstone/mudstone ratio into the very sandstone-rich portion is interpreted as the result of the progressive flow stripping of the fine-grained component of the turbidity currents (Fig. 1A; Tomasso 2001). Overlying this, erosional downcutting is interpreted to have resulted from incision into the basin fill during a period of bypass. The lowermost, fine-grained interval in the southern part of the northern sub-basin is interpreted as the time-equivalent products of the phase of flow stripping in the southern basin (Fig. 1A). The Coyer Canyon represents an incised interbasinal canyon fill. The lowermost channels at the contact with the underlying hemipelagic mudstones record incision during bypass. The overlying succession records backfilling, followed by aggradation of sand bodies with both channelized and sheet geometries.

The Taveyannaz Sandstones were deposited in two sub-basins at the frontal margins of the submarine Alpine thrust wedge (Sinclair 1992). The Inner Basin is confined to the north, as revealed by onlap and pinch-out of the infill (Fig. 1B) and has a maximum recorded thickness of 140 m. The facies of the Inner Basin are dominated by at least 12 tabular, very thick-bedded sandstones (up to 10 m thick), with associated thick mudstone caps. These beds are predominantly structureless, with localized planar bedding. Sandstone injections up to 0.6 m are locally developed in the thick mudstone intervals. Sandstone/mudstone ratios are approximately 40% in the lower portions of the basin, increasing to 80% towards the top of the succession; this is linked to a loss of the thick mudstone intervals and increased amalgamation of sandstone beds (Fig. 1B). Capping the Inner Basin are a succession (> 20 m thick) of very thin-bedded siltstones and mudstones with starved-ripple lamination and bioturbation-induced mottling. These fine-grained facies are locally intensely deformed (Sinclair 1992). The Outer Basin succession is at least 240 m thick. It is characterized by sandstone packages ranging from 5 to 100 m thick comprising intensely amalgamated medium- to thick-bedded sandstones. Separating these packages are medium- to thin-bedded sandstone–mudstone couplets.

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The Inner Basin has been interpreted as a confined sub-basin with the very thick-bedded sandstone–mudstone couplets recording flow ponding (Sinclair 1992). It is proposed that the increased sandstone/mudstone ratios towards the upper parts of the basin record flow stripping over the confining barrier. The fine-grained succession that caps the Inner Basin is interpreted as a record of abandonment following filling of the sub-basin (see model below). The Outer Basin is interpreted as having been deposited at the base of slope, bounded to the south by the thrust-induced topography of the slope (Sinclair 1992). Here, we interpret the amalgamated sandstone packages as a result of a hydraulic jump at the base of slope (see model below).

**A DEPOSITIONAL MODEL**

On the basis of the above observations and an understanding of turbidity current dynamics and their deposits, a simplified depositional model for confined, intraslope turbidite basins is proposed. The characteristic basin morphology for the model is of two basins perched one above the other on a submarine slope, separated by an interbasinal high (Fig. 2). Importantly, in this model the basin-bounding slopes are static and do not evolve through time; this is in contrast to some of the Gulf of Mexico sub-basins, where syndepositional slope growth may be as fast as 10 mm/yr (Prather 2000). The intention is to keep the initial model as simple as possible. The sediment transport processes were surge-type, mixed-grain-size turbidity currents that discharged into the upper sub-basin via a single point source. The kinetic energy of these currents was insufficient to surmount the initial height of the interbasinal high. It is recognized that sedimentation in the Gulf of Mexico was punctuated by debris flows, but again, the parsimonious approach precludes their inclusion.

It is proposed that the depositional evolution of this system can be divided into four phases (Fig. 2). These phases record the dominant response of the incoming turbidity currents to the basin morphology as the basin progressively fills.

**Phase 1—Flow Ponding (Fig. 2A)**

The earliest recognition of flow ponding of turbidity currents in modern settings was from fault-bounded basins on the Mid-Atlantic Ridge (Van Andel and Komar
Ancient examples have been interpreted from the Ordovician Cloridorme Formation, Quebec (Pickering and Hiscott 1985), Eocene Flysch of Middle Dalmatia (Marjanic 1990), and the Neogene deposits of the Sorbas and Tabernas basins, southeast Spain (Haughton 1994, 2000).

The notable characteristics of "contained turbidites" (Pickering and Hiscott 1985) as documented from the examples listed above include: (1) the presence of thick mudstone caps overlying sandstone beds; (2) complex paleocurrent directions; (3) dominance of thick beds; (4) complex grading patterns; (5) evidence of dewatering; and (6) onlap of sheet-like bed geometries. Many of these characteristics are observed from the examples described previously.

In order for flow ponding to take place, the confining basin must be surrounded by topographic barriers that are sufficient to prevent turbidity currents surmounting them. Evaluation of the controls on the ability of a turbidity current to surmount an opposing barrier were first considered using numerical calculations and flume tank experiments (Muck and Underwood 1990). Flow thickness was determined as the primary control on run-up distance. For a subcritical, uniform density current, run-up distance was approximated as 1.5 times the thickness of the flow head. Observations from the modern oceans suggest that this distance may be several hundreds of meters (Muck and Underwood 1990). More exact calculations of run-up distances will require more complex integration of velocity and density profiles within flows (Kneller and McCaffrey 1999).

Once the turbidity current runs up an opposing slope, the kinetic energy of the current will be transformed into potential energy able to drive a reflected flow component. The interference between the incident and reflected flow generates an internal bore located at the base of the slope (Edwards 1993). The reflection of turbidity currents off opposing slopes is interpreted as the cause of many of the sedimentary

Fig. 2.—Depositional model for the progressive infill of a confined turbidite basin and associated deposits at the base of the slope of a lower basin. See text for descriptions of the four stages.
characteristics listed above from the Annot Sandstones such as variable paleocurrent indicators and variable grading patterns (Pickering and Hiscott 1985). Kneller and McCaffrey (1999) also explain the abrupt transition from massive coarse sandstones up into thinned sandstones with variable paleocurrent directions as a consequence of density stratification within ponded turbidity currents. In the upstream portion, the lower, higher-density portion of the flow accelerates, rapidly resulting in rapid sediment fallout; in contrast, the overlying, lower density portion is reflected and deflected by the bounding topography.

An additional consequence of the rapid sediment accumulation rates of alternating thick sands and muds during this phase is the increased probability of fluid over-pressure and associated sediment remobilization. This is recorded by the sandstone injections in the Taveyannaz Sandstones and the extensive slumping and soft sediment deformation in the “J” sands of the Bullwinkle Basin, Gulf of Mexico.

Phase 2—Flow Stripping (Fig. 2B)

The process of flow stripping records the partial surmounting of a barrier by the uppermost, lower-density fraction of a turbidity current. It was first recognized as a potentially important process in meandering submarine channels where flows may partially surmount the surrounding levees (Piper and Normark 1983). Flume tank experiments involving flow over obstacles (Alexander and Morris 1994), although difficult to scale, have yielded insight into the possible depositional responses. Such experiments suggest thick sediment accumulations immediately upstream of obstacles have yields insight history into the possible depositional responses. Such experiments suggest thick sediment accumulations immediately upstream of opposite, thick sediment accumulations immediately upstream of opposite, thick sediment accumulations immediately upstream of opposite slopes, with much thinner deposits accumulating downstream of the topography. In the upstream portion, the lower, higher-density portion of the flow accelerates, rapidly resulting in rapid sediment fallout; in contrast, the overlying, lower density portion is reflected and deflected by the bounding topography.

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The implications are that during the progressive filling of the upper, confined basin, the effective barrier height will be less than the potential run-up distance of the incoming turbidity currents. At this time, it is predicted that there will be a sorting of grain-size populations, with the coarser fraction preferentially preserved in the upper confined basin, and the finer component stripped off and transported into the lower basin (Fig. 2B). The finer portion of the flow would utilize any possible low points on the intervening high, thus potentially initiating a conduit into the lower basin.

The increasingly sandstone-rich nature of the upper part of the southern sub-basin of the Annot Sandstones and the Inner Basin of the Taveyannaz Sandstones is interpreted to have resulted from flow stripping. The detached fine-grained equivalent deposits are represented by the brown, siliciclastic mudstones that drape the lower part of the proximal northern sub-basin (Fig. 1B). This process has also been proposed for the Troika Field in the Gulf of Mexico (Horine et al. 2000) and may be responsible for the increasing sand content in the “J” sands of the Bullwinkle Basin (see fig. 8 in Holman and Robertson 1994). However, the Auger Basin does not record any significant upward change in sand content in the ponded facies assemblage (Prather et al. 1998), suggesting other influences at this time (see below).

Phase 3—Flow Bypass (Fig. 2C)

When the upper basin is sufficiently filled with sediment, the break of slope that defined the margin of the upper basin becomes healed (Prather et al. 1998), and the opposing interbasinal high is predominantly buried. With no bounding topography to trap the incoming turbidity currents, the bulk of the sediment is bypassed. This will occur either by incision and bypass over the confining basin (Fig. 2C) or by its abandonment and redirection of the incoming flows away from the confined basin (Fig. 2Ci).

The transition from sheet sandstone bodies towards more channelized geometries within an upper basin is characterized by incision. The transition from phase 2 to phase 3 is associated with a progressive increase in the sediment texture, volume, and velocity of the turbidity currents able to travel over the outer confining high, until the threshold for erosion is reached. At this time, incision of the outer high will commence, thus initiating an interbasinal canyon (Satterfield and Behrens 1990). Progressive downcutting of the interbasinal canyon will define a baselevel for the upper basin that is lower than the level to which the sediments of phases 1 and 2 accumulated. The result is progressive incision into the upper parts of the confined basin succession (Fig. 2C). The erosional scour in the upper deposits of the southern sub-basin of the Annot Sandstones is interpreted as a record of this process (Fig. 1A). Similarly, the incised channels at the base of the Coyer Canyon are interpreted as a record of incision during stripping (Prather et al. 1998).

An alternative response to the decrease in accommodation space during the end of phase 2 is the switching of the sediment routing system away from the upper basin. In this case, the upper, confined basin will be abandoned, resulting in fine-grained, condensed, overbank sediments being deposited; this is the interpretation for the thick accumulation of mudstones on top of the Inner Basin of the Taveyannaz Sandstones (see above).

During flow bypass, the bulk of sediment deposition will occur in the lower basin. The depositional processes at the most proximal parts of the lower basin will be comparable to those seen at the base of the continental slope. The abrupt reduction in gradient at the base of the interbasinal high will lead to the rapid deceleration of the turbidity currents and a likely hydraulic jump from a supercritical to a subcritical flow. Hydraulic jumps at the base of submarine slopes are thought to lead initially to erosion (Lee et al. 1999) followed by rapid sediment fallout near the base of slope (Garcia 1993). Evidence of these conditions should be recorded by the proximal sediments of the lower basin, where they onlap the interbasinal high (Fig. 2C). In the Annot Sandstones, this process is recorded by the amalgamated and dewatered toe-of-slope deposits that onlap southwards immediately north (distal) of the interbasinal Coyer Canyon (Fig. 1A). Similarly, the high degree of erosional amalgamation in the sand packages of the Outer Basin of the Taveyannaz Sandstones are interpreted as a result of these processes.

Phase 4—Blanketing (Fig. 2D)

By the time the lower basin is filled, the depositional gradient of the system is reduced. Where bypass has occurred by incision, the interbasinal canyon will become partly or wholly backed by sediment accumulation in the lower basin, and so the local base level for the upper basin will rise, leading to renewed sediment accumulation. This is the situation seen in the filled basins of the upper slope of the Gulf of Mexico, where channel levee systems aggrade over basins and link with interbasinal canyons that incise into upflling interbasinal highs (Satterfield and Behrens 1990). It is also recorded in the infill of the Coyer Canyon in the Annot Sandstones: the depositional setting for these deposits is channel–sheet complexes (Fig. 1A). Notably, the lowermost infill of the Coyer Canyon is marked by an interval of condensation that caps the onlapping deposits of the northern sub-basin (Fig. 1A). It is proposed that this records the reduction in gradient, and the associated development of meandering channel systems, with condensed overbank tines. Similar processes have been recorded towards the top of the ponded assemblages of the Gulf of Mexico (Prather et al. 1998).

DISCUSSION

This contribution has attempted to draw generalities about the depositional behavior of confined turbidite basins regardless of other important controlling factors such as tectonic and geographic setting, sea-level change, or sediment texture. Nor does it treat the potentially complex infill histories of partially confined basins, of which there are numerous examples (e.g., Yielding and Apps 1994). As such it is an end-member model that is heavily influenced by the author’s experience in Alpine basins. In this context it is important to note the significant differences that exist between the Alpine and Gulf of Mexico settings. The former represents a foreland basin with a tectonically active source terrain delivering sand-rich sediment over relatively short distances (Sinclair 2000). In contrast, the Gulf of Mexico is a passive margin fed by a large, mud-rich river system draining a large portion of North America (Prather et al. 1998). However, the ability to derive general principles based on sedimentary processes from such differing basin settings strengthens the generic significance of these observations.

Well-dated basin-fill successions in the Gulf of Mexico have enabled sedimentological descriptions of sea-level-induced depositional sequences (Yielding and Apps 1994; Prather et al. 1998). The confined-basin sequence described here is of a similar magnitude to third-order depositional sequences that record the growth of basin-floor fans during relative sea-level fall and lowstand conditions (Posamentier et al. 1991). It is important to note that the confined basin sequence, as proposed, is based on a constant and uniform sediment supply and is controlled only by the evolving geometry of the basin. Periods of time when sediment supply and caliber were changing in response to climate or sea-level change would modify the confined-basin sequence character. For example, the combination of influences may help to explain the lack of any change in sand/mud ratio in the upper part of the ponded facies assemblage of Prather et al. (1998).

The stacking of confined basin sequences is achievable only with syndepositional relative uplift of the topography of the confining basin floor. Evidence for this has not been documented from the Annot and Taveyannaz Sandstones, where the basin-floor topography remained relatively static during basin filling. However, Holman and Robertson (1994) indicate the role of syndepositional growth of the confining topography of the Bullwinkle Basin during deposition of the “1” sand. Evidence for syndepositional uplift of the basin topography should be identifiable from growth strata and onlap–offlap relationships towards the margins of the basin (Fig. 3). As identified in the Bullwinkle Basin, syndepositional uplift is also associated with in-
increased slumping, debris flows, and soft-sediment deformation (Holman and Robertson 1994).

CONCLUSIONS

On the basis of a synthesis of Alpine outcrop studies and the subsurface record from the Gulf of Mexico, it is proposed that the infill of intraslope, confined turbidite basins can be characterized by four phases: Phase 1, flow ponding; phase 2, flow stripping; phase 3, flow bypass; phase 4, blanketing.

Assuming a steady sediment supply and caliber, and no change in sea level, the facies assemblages of the four phases is predictable and should stack to form a confined basin sequence. The base of a sequence commences with laterally continuous, ponded sandstones and mudstone facies, and evidence of sediment remobilization. Continuing up the succession, the sequence should exhibit an increase in the sand-to-mud ratio caused by progressive flow stripping. This will then be capped by channeling or abandonment when the upper confined basin is filled to its spill point. Time-equivalent facies in the lower basin should comprise a fine-grained drape of the basin floor recording accumulation of the flow-striped component from the upper basin (phase 2). During phases 3 and 4 there is an upward increase in sand content in the lower basin, with base-of-slope onlap recording a combination of erosion and rapid sedimentation (Fig. 2). The intervening high will be incised and blanketed during phases 3 and 4, respectively.

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