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TURBIDITE ARCHITECTURE IN PROXIMAL FORELAND BASIN-SYSTEM DEEP-WATER DEPOCENTERS: INSIGHTS FROM THE CENOZOIC OF WESTERN EUROPE

Jacob A. COVAULT[*)] & Stephan A. GRAHAM

KEYWORDS

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Department of Geological and Environmental Sciences, Stanford University, Stanford, CA, 94305-2115 USA

[*)] Corresponding author, jcovault@stanford.edu

ABSTRACT

Proximal foreland basin-system depocenters (i.e., foredeep-margin and wedge-top depozones) contain prolific hydrocarbon reserves; however, there has been considerably less research over the last decade focused on such structurally and stratigraphically complex settings. Rather, recent turbidite-reservoir studies have focused on sedimentation associated with slope channel-levee systems and intraslope basins in passive continental-margin settings. However, significant differences in tectonic deformation and submarine topography between foreland basin systems and passive-margin settings foster the development of distinctively different stratigraphic architecture. We review turbidite systems and associated reservoirs in Cenozoic European proximal foreland basin-system deep-water depocenters in Italy, Spain, France, and Austria. Foredeep-margin stratigraphic architecture includes erosional unconformities and packages of turbidites up to hundreds of meters thick in pockets of slope accommodation created by canyon-channel systems and/or slump scars. Wedge-top stratigraphic architecture generally includes relatively fine-grained mass transport-complex deposits at the base of steep basin margins adjacent to thrust sheets and upward-fining and -thinning turbidites stratigraphically partitioned by mass transport-complex deposits across flat, unconfined basin floors. Turbidite-architecture development is primarily dependent on tectonic deformation and topography inherent to proximal foreland basin systems. Oblique-to-thrust-front-oriented structures facilitate the development of sediment conduits from hinterland source areas to pockets of accommodation across steep foredeep-margin slopes and axial foredeeps. Syn-depositional fold-thrust belt development can create wedge-top accommodation in which appreciable volumes of turbidites accumulate. Syn-depositional deformation also creates wedge-shaped turbidite-reservoir architecture (i.e., growth strata) and initiates sediment failure. Submarine topography controls sediment gravity-flow behavior by promoting bypass or localizing sediment deposition. Common characteristics and controls of turbidite architecture in proximal foreland basin systems are compared to widely used turbidite-reservoir models from Neogene Gulf of Mexico salt-withdrawal basins. We present a seismic-reflection-based turbidite-reservoir exploration strategy for proximal foreland basin-system depocenters, which can be applied to oil and gas exploration in analogous structurally complex, collisional settings.

Depocenter von proximale Vorlandbecken-Systemen, wie wie etwa Ablagerungszonen am Vortiefenrand und Becken auf dem Überschiebungskeil, beinhalten produktive Kohlenwasserstoffreserven. Diese strukturell und stratigraphisch komplexen Ablagerungskonstellationen wurden in der letzten Dekade allerdings selten untersucht. Stattdessen konzentrierten sich die neuere Studien zur Reservoirs von Turbiditen auf Ablagerungen verbunden mit tiefmarinen Hangrinnen-Dammsystemen und Intra-Hangbecken an passiven Kontinentalrändern. Die signifikanten Unterschiede in tektonischer Deformation und submariner Topographie von Vorlandbeckensystemen und passiven Kontinentalrändern bewirken allerdings unterschiedliche und distinkte stratigraphische Architekturen. Wir geben einen Überblick über Turbiditsysteme und damit verbundene Reservoirs in Tiefwasser-Depocenters von känozoischen europäischen proximalen Vorlandbeckensystemen in Italien, Spanien, Frankreich und Österreich. Die stratigraphische Architektur von Ablagerungen in Vortiefenrändern beinhalten erosive Diskordanzen und Turbiditabfolgen mit mehreren hunderten Meter Mächtigkeit, abgelagert in in kleinen Hang-Akkomodationsbecken, welche durch Canyon-Rinnen-Systemen und/oder Rutschungen entstanden sind. Die stratigraphische Architektur am Top des Überschiebungskeils beinhaltet hauptsächlich zweierlei Ablagerungen: a) relativ feinkörnige Sedimente von Massentransportkomplexen, welche sich am Fuß von steilen Beckenrändern befinden, die durch Überschiebungen entstandenen sind, und b) upward-fining und –thinning Turbiditabfolgen, die den ebenen, freien Beckenboden kennzeichnen, aber zum Teil durch Massentransportkomplexen zerteilt sind,. Die Architektur der Turbiditablagerungen sind im Wesentlichen abhängig von tektonischer Deformation und Topographie, also von inhärenter Faktoren von Vorlandbeckensysteme.. Schräg zur Überschiebungsfront angeordnete Strukturen erleichtern das Entstehen von Sedimenttransportwegen vom Hinterland zu den kleinräumigen Sedimentationsbecken am Hang des Vortiefenrands und zur Beckenachse der Vortiefe. Synsedimentäre Aktivität im Überschiebungsgürtel kann Akkomodationsraum auf dem Überschiebungskeil entstehen lassen, in dem nennenswerte Volumina von Turbiditen abgelagert werden. Synsedimentäre Deformation bedingt auch die keilförmige Turbidit-Reservoirarchitektur (growth strata) und kann zur Instabilität der Ablagerungen führen. Die submarine Topographie kontrolliert das Verhalten gravitativer Sedimentströmungen durch Bypass oder das Bereitstellen von lokalen Ablagerungszonen. Die allgemeinen Charakteristika und kontrollierenden Faktoren der Turbiditarchitektur in proximalen Vorlandbeckensystemen werden mit den weitverbreiteten Modellen von neogenen Turbiditreservoirn aus den Salzauslaugungsbecken im Golf von Mexico verglichen. Wir präsentieren eine auf Reflexionsseismik beruhende Explorationsstrategie für Turbiditreservoire in Depocenter von proximalen Vorlandbeckensystemen. Diese kann- für die Öl- und Gasexploration in analogen, strukturell komplexen Kollisions-Szenarios angewandt werden.

1. INTRODUCTION

Exploration for turbidite reservoirs in proximal foreland basin-system depocenters is increasingly common (Meeting on fold-thrust belt exploration abstract book, 2008). Cataloging stratigraphic architecture and interpreting developmental controls of turbidite systems in such settings is extremely useful for application in analogous frontier areas (especially as a result of the structural and stratigraphic complexities inherent to fold-thrust belts and foredeep margins; Graham, 2008). Proximal foreland basin-system depocenters are created as a result of lithospheric plate movements and the sedimentary response to such movements, and include accommodation on the back of thrust sheets in the wedge-top depozone, and pockets of accommodation on foredeep-margin slopes (DeCelles and Giles, 1996; Fig. 1). The wedge-top depozone extends toward the foreland to the limit of deformation associated with the frontal tip of the underlying orogenic wedge (DeCelles and Giles, 1996; Fig. 1). Sediment accommodation in the wedge-top depozone is the net result of competition between regional, load-driven subsidence, and regional and local uplift of the orogenic wedge (DeCelles and Giles, 1996). Distinctive topographic features of the wedge top include piggyback basins (Ori and Friend, 1984; Ricci Lucchi, 1986) and extensive sediment conduits/drainage systems in the interiors of fold-thrust belts (Burbank et al., 1986; Hirst and Nichols, 1986; Homewood et al., 1986; Massari et al., 1986; Ori et al., 1986; Ricci Lucchi, 1986; Coney et al., 1996; Vincent and Elliott, 1997; DeCelles and Giles, 1996; Covault et al., 2008). In deep-water environments, wedge-top sedimentary fill typically includes synorogenic packages of chaotic mass transport-complex deposits, which exhibit numerous unconformities and evidence of progressive deformation (Ori et al., 1986; Ricci Lucchi, 1986; DeCelles and Giles, 1996; Covault et al., 2008).

The foredeep margin merges with the wedge-top depozone forward of the frontal tip of the orogenic wedge (DeCelles and Giles, 1996; Fig. 1). The axial foredeep depozone has been the focus of most foreland basin-system studies (e.g., Covey, 1986; Sinclair and Allen, 1992; DeCelles and Giles, 1996; De Ruig and Hubbard, 2006; Hubbard et al., 2008a, 2008b), and sediment accommodation is primarily a response to loading by the adjacent orogenic wedge and sediment eroded from the wedge, as well as subsurface loading (Jordan, 1981; Royden and Karner, 1984; Royden, 1993; Jordan, 1995; DeCelles and Giles, 1996). The relatively steep foredeep margin has been generally characterized as exhibiting evidence of sediment bypass and widespread unconformities (DeCelles and Giles, 1996).

European proximal foreland basin-system depocenters and their sedimentary fill were the subjects of seminal research regarding the interplay of tectonic deformation and deep-water sedimentation (e.g., studies of Apenninic turbidites by Mutti 1985, 1992; and Ricci Lucchi, 1985, 1986, 2003); however, the turbidite-reservoir studies during the last decade have focused on sedimentation associated with slope channel-levee systems and intraslope basins in passive continental-margin settings (Mutti et al., 2003). Recent studies have been particularly focused on prolific Neogene turbidite reservoirs and deposits in salt-withdrawal basins in the Gulf of Mexico (e.g., Satterfield and Beherens, 1990; Prather et al., 1998; Beaubouef and Friedmann, 2000; Booth et al., 2000; and Mallarino et al., 2006). These tectonically dynamic basins develop as a result of the interplay of sedimentation and salt diapirism (Fails, 1990; Diegel et al., 1995; Booth et al., 2000; Twichell et al., 2000), which produce local circular to elliptical depocenters. Basin fill

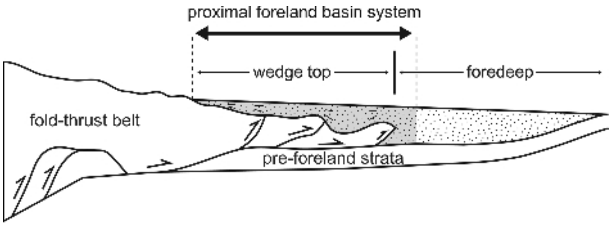

FIGURE 1: Schematic cross section of a proximal foreland basin system (highlighted in gray; axial foredeep included for context). Progressive deformation in the wedge-top depozone is represented by short fanning lines associated with thrust tips. Modified from DeCelles and Giles (1996).

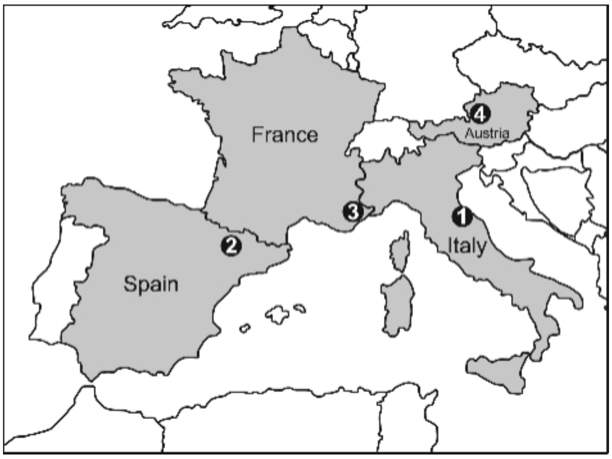

FIGURE 2: Locations of Cenozoic European proximal foreland basin-system deep-water depocenters and turbidite systems therein. (1) Miocene Marnoso-arenacea foredeep and Oligocene Loiano and Antognola wedge-top depocenters, Apenninic foreland basin system, Italy. (2) Eocene Ainsa wedge-top basin, south-central Pyrenean foreland basin system, Spain. (3) Eocene-Oligocene Annot wedge-top basin, western Alpine foreland basin system, France. (4) Oligocene-Miocene foredeep-margin and wedge-top depocenters, Molasse foreland basin system, Austria.

comprises isopachous packages of coarse-grained turbidite sandstone or sand stratigraphically partitioned by fine-grained mass transport-complex and hemipelagic deposits (Beaubouef and Friedmann, 2000; Booth et al., 2000; Mallarino et al., 2006). Significant differences in tectonic deformation and submarine topography exist between foreland basin systems and passive continental-margin settings. This variation fosters the development of distinctively different reservoir architecture. Therefore, recent models of turbidite reservoir development in Gulf of Mexico salt-withdrawal basins are unlikely to accurately predict reservoir quality in a tectonically and topographically dissimilar foredeep-margin or wedge-top depozone of a foreland basin system (see also discussions of Mutti et al., 2003; and Covault et al., 2008).

In this paper, we review Cenozoic European proximal foreland basin-system deep-water depocenters and the turbidite systems and associated reservoirs therein (Fig. 2). Common architectural characteristics and developmental controls of turbidite systems are discussed and compared to widely cited models from recent studies of Neogene Gulf of Mexico salt-withdrawal basins (e.g., Gulf of Mexico models have been recently cited by Argent et al., 2000; Sinclair, 2000; Sinclair and Tomasso, 2002; Grecula et al., 2003; Underwood et al., 2003; Adeogba et al., 2005; Shultz and Hubbard, 2005; Anderson et al., 2006; De Ruig and Hubbard, 2006; and Gee et al., 2007). We also present a seismic-reflection-based turbidite-reservoir exploration strategy for proximal foreland basin-system depocenters, which can be applied to analogous structurally complex, collisional settings.

2. Turbidite Architecture in Cenozoic European Proximal Foreland Basin-System Depocenters

2.1 Miocene Marnoso-arenacea foredeep and Oligocene Loiano and Antognola wedge-top depocenters, Apenninic foreland basin system, Italy

The Apenninic fold-thrust belt and associated foreland basin system formed as a result of compression and shortening of the African-Adriatic continental margin since the Oligocene (Ricci Lucchi, 1986; Argnani et al., 2001; Cibin et al., 2004). Ricci Lucchi (1986) characterized turbidites in major basins of the foredeep depozone and minor or satellite basins on the wedge top of the Apenninic fold-thrust belt (Figs. 2, 3, and 4; see also Cibin et al., 2004). Complexes of turbidites (i.e., entire basin-filling successions; cf., turbidite depositional-unit hierarchy of Mutti and Normark, 1987; see also Cibin et al., 2004) in major basins have volumes of 3000-30000 km^3 and are hundreds of kilometers long and tens of kilometers wide, whereas minor basins are filled with volumes on the order of tens to hundreds of cubic kilometers and are little more than 10 km in diameter (Ricci Lucchi, 1986).

The Miocene Marnoso-arenacea Formation accumulated in the Apenninic foredeep (volume of nearly 30000 km^3 and local thickness in excess of 3000 m; Ricci Lucchi, 1986; Fig. 3). Ricci Lucchi and Valmori (1980) and Ricci Lucchi (1986) characterized Marnoso-arenacea turbidites as laterally extensive (individual beds correlatable across tens of kilometers), fine-grained sandstone interbedded with hemipelagic mudstone (10-20% of total volume), and interpreted them as having been deposited in basin plain and submarine fan fringe environments in the axial foredeep (see also Talling et al., 2007). The foredeep margin is not extensively exposed; however, the culmination of Marnoso-arenacea deposition is represented by multistory channel-fill bodies (individually tens of meters thick; composite bodies up to hundreds of meters thick) and mass transport-complex deposits (sequence T2 of Ricci Lucchi, 1986), which reflect sediment bypass and mass-wasting processes in a relatively proximal slope environment (Gandolfi et al., 1983; Ricci Lucchi, 1986; Fig. 4). Channel fill includes sand and gravel from distant Apenninic and Alpine source areas, and intraformational clasts are rare, but present (Ricci Lucchi, 1986). Ricci Lucchi (1986) identified several structures perpendicular to the Apenninic thrust front that controlled significant sediment conduits to the foredeep (see also Boccaletti et al., 1990; Figs. 3 and 4).

Minor or satellite basins on the wedge top of the Oligocene Apenninic fold-thrust belt include the Loiano and Antognola basins, which are filled with sediment gravity-flow deposits hundreds of meters to one kilometer thick (Ricci Lucchi, 1986; Figs. 3 and 4). Basin fill exhibits a lateral facies transition from relatively fine-grained mass transport-complex deposits at the base of steep satellite-basin margins adjacent to thrust sheets to upward-fining and -thinning turbidites across flat basin floors (Ricci Lucchi, 1986). Lateral stratigraphic thickness changes are dramatic (i.e., from >1000 m to <100 m across <5 km), and outward wedging of sedimentary bodies (i.e., growth strata)

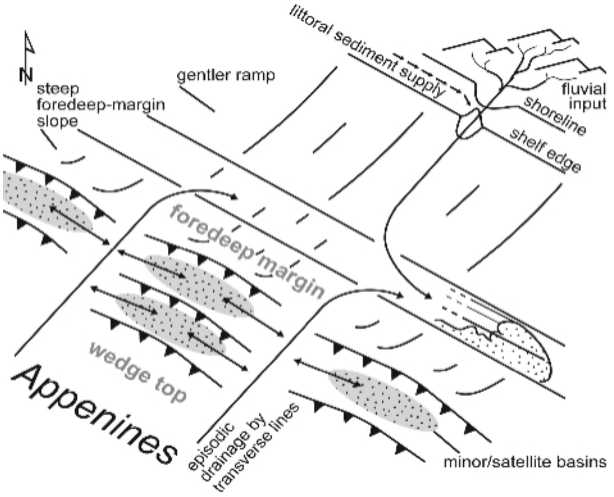

Figure 3: Schematic representation of Cenozoic Apenninic foredeep and wedge-top basins and dispersal patterns. The subsiding foredeep is flanked by a submarine wedge top to the southwest; sediment supply includes contributions from the Apenninic hinterland and distant Alpine sources to the north and northeast (Ricci Lucchi, 1985, 1986). Modified from Gandolfi et al. (1983), Ricci Lucchi (1985, 1986), and Cibin et al. (2004).

indicates syn-depositional deformation. Ricci Lucchi (1986) attributed depocenter locations on the wedge top to persistent structures perpendicular to the Apenninic thrust front, which might have created accommodation as a result of subsidence and initiated sediment gravity flows as a result of episodic pulses of tectonic activity (Figs. 3 and 4).

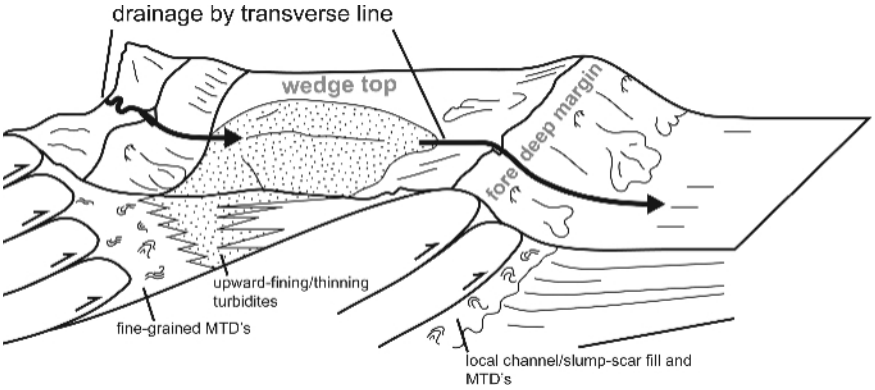

Figure 4: Detailed schematic representation of stratigraphic architecture in Cenozoic Apenninic foredeep-margin and wedge-top depocenters. The wedge-top depocenter is a satellite basin (i.e., piggyback basin), which exhibits a transition from relatively fine-grained mass transport-complex deposits (MTD's) at the base of the steep piggyback-basin margin to upward-fining and -thinning turbidites across the flat basin floor. The foredeep margin exhibits local channel/slump-scar accommodation filled with turbidites and mass transport-complex deposits (MTD's) at the base of slope. Consult the text and Ricci Lucchi (1986) for more information regarding details of stratigraphic architecture. Modified from Ricci Lucchi (1985).

2.2 Eocene Ainsa wedge-top basin, south-central Pyrenean foreland basin system, Spain

The south-central Pyrenean foreland basin system formed during Late Cretaceous to early Miocene convergence between the Iberian and European plates (Coney et al., 1996). The Eocene Ainsa basin (several kilometers wide and tens of kilometers long; Mutti, 1985; Fernández et al., 2004) originated as a foredeep; however, during the middle Eocene, the basin was incorporated into the hanging wall of a forward-propagating thrust fault and evolved into a piggyback basin (i.e., as a result of piggyback thrust propagation; Dahlstrom, 1970; Butler, 1982; cf., piggyback basins of the Ferrara thrust system in the Po basin; Ori and Friend, 1984; Fernández et al., 2004; Figs. 2 and 5).

The extensively studied Ainsa basin fill comprises six relatively coarse-grained turbidite systems (100-200 m thick) separated by thin-bedded sandstone and mudstone: the Arro-Charo, Gerbe, Banaston, Ainsa, Morillo, and Guaso systems (Mutti, 1985; Pickering and Corregidor, 2005a, 2005b; other studies include Clark, 1995; Clark and Pickering, 1996; Fernández et al., 2004; Fig. 5). Pickering and Corregidor (2005a, 2005b) characterized mass transport-complex deposits in the Ainsa basin, which accumulated at the base of relatively steep basin-margin slopes and stratigraphically partitioned relatively sand-rich, amalgamated, channel-filling turbidites overlain by finer-grained, thin-bedded sandstone and mudstone. Fernández et al. (2004) characterized growth strata of the turbidite systems filling the Ainsa basin. Mutti (1985) and Pickering and Corregidor (2005a, 2005b) attributed Ainsa stratigraphic architecture to episodic pulses of tectonic deformation during the middle Eocene, which initiated sediment gravity flows across basin margins (Mutti, 1985). Upward-fining and -thinning turbidite architecture developed as a result of limited coarse-grained sediment accumulation/recharge in the shelf-edge staging area between episodes of deformation (Mutti, 1985; Fig. 5).

2.3 Eocene-Oligocene Annot wedge-top basin, western Alpine foreland basin system, France

Wedge-top basins in southeastern France developed during Eocene-Oligocene southwestward migration of the Alpine orogenic front as a result of collision between the European and African-Adriatic plates (Artoni and Meckel, 1998; Evans and Elliott, 1999; Apps et al., 2004; Figs. 2 and 6). Sinclair (2000) reconstructed the paleotopography of the wedge-top Annot basin, and characterized its sedimentary fill (i.e., the Annot Sandstone, which was the focus of seminal turbidite research; e.g., Bouma, 1962; see also Joseph and Lomas, 2004; Figs. 2

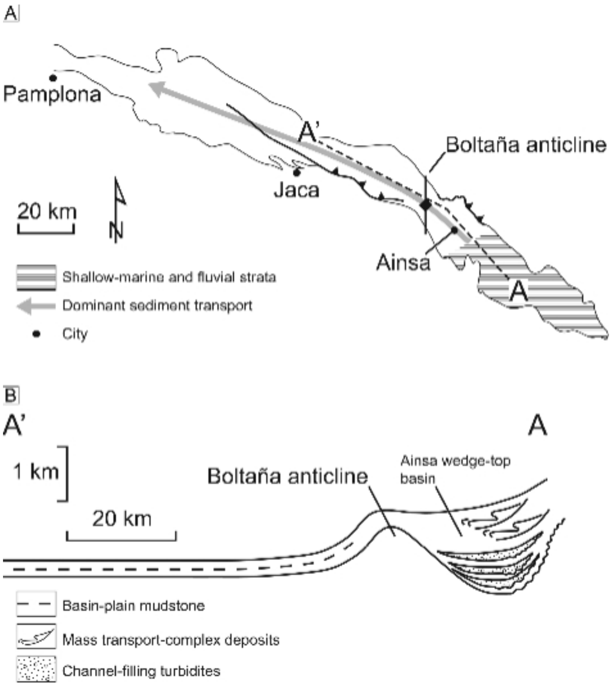

Figure 5: South-central Pyrenean foreland basin system outcrop area and schematic cross section of middle-upper Eocene stratigraphy. (A) South-central Pyrenean foreland basin system outcrop area. Dashed black line represents location of cross section in B. (B) Schematic cross section of middle-upper Eocene stratigraphy. Upward-fining and -thinning Ainsa basin fill, including relatively coarse-grained turbidite systems stratigraphically partitioned by mass transport-complex deposits. Modified from Mutti (1985).

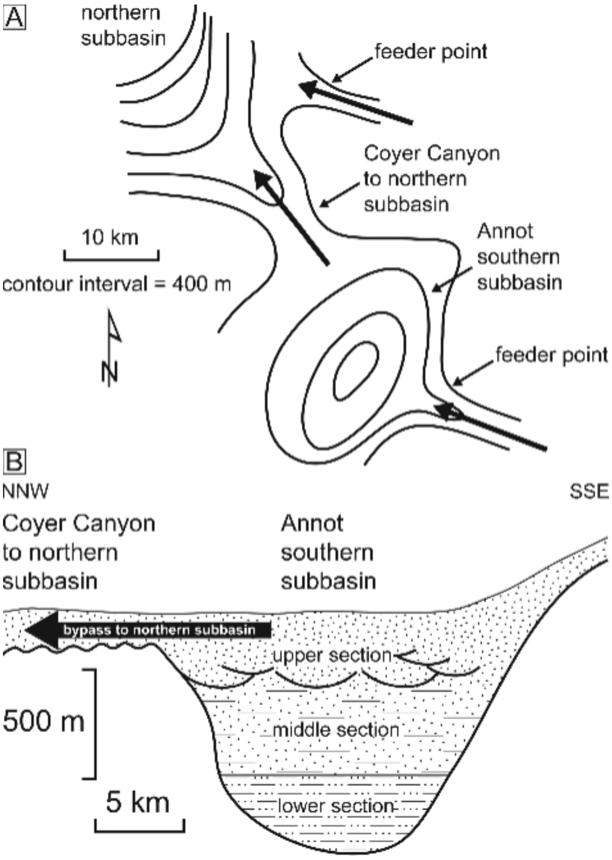

Figure 6: Schematic representation of the Annot southern subbasin. (A) Topography of Annot southern and northern subbasins immediately prior to deposition of the Annot Sandstone. The southern subbasin was sourced from the south and east (Stanley, 1961, 1980). Modified from Sinclair (2000). (B) Annot southern subbasin turbidite fill. Lower section includes fine-grained, structureless turbidites interbedded with hemipelagic mudstone and mass transport-complex deposits. Middle section includes interbedded, coarser-grained turbidites with better-developed grading and capped with thin mudstone units. Upper section includes thick-bedded, amalgamated, massive, coarse-grained turbidites and evidence of sediment bypass. Concave-up features in the upper section are scours and channels indicating bypass. Modified from Sinclair and Tomasso (2002).

and 6). The Annot basin included two subbasins (northern and southern subbasins) separated by a topographic high, which was incised by a subbasin-linking canyon (Coyer Canyon; Sinclair, 2000; Fig. 6). The subbasins are up to 20 km in diameter with depths approaching 1 km (Sinclair and Tomasso, 2002; Fig. 6).

The sedimentary fill of the axial regions of subbasins is organized into upward-coarsening and -thickening stratigraphic successions up to one kilometer thick (Sinclair, 1994; Sinclair, 2000; Sinclair and Tomasso, 2002; Fig. 6). The lower section of the southernmost subbasin is composed of a package of fine-grained, structureless turbidites interbedded with hemipelagic mudstone and mass transport-complex deposits (Sinclair, 2000; Sinclair and Tomasso, 2002). Turbidites include intraformational mudstone clasts, which imply a nearby source area (e.g., a steep basin-margin slope; Sinclair and Tomasso, 2002). The middle section of the subbasin includes a package of interbedded, coarser-grained turbidites with better-developed grading and capped with thin mudstone units (Sinclair, 1994; Sinclair and Tomasso, 2002). The upper section predominantly includes thick-bedded, amalgamated, massive, coarse-grained turbidites and evidence of sediment bypass (Sinclair and Tomasso, 2002). Upward-coarsening and -thickening basin-filling successions are attributed to phases of: (1) sediment gravity-flow ponding, when flows were completely confined by basin margins (represented by the lower section in the southern subbasin); (2) followed by flow stripping, when the finer-grained parts of flows were not confined by basin margins and deposited elsewhere (represented by the middle section); and (3) flow bypass as a result of complete filling of subbasin accommodation (represented by the upper section; Sinclair and Tomasso, 2002; Fig. 6). Marginal regions, adjacent to deltaic sediment source areas, exhibit more chaotic debris-flow and mass transport-complex deposits and evidence of sediment bypass (Sinclair, 2000). Syn-depositional deformation does not appear to have significantly influenced Annot turbidite-system geometry (i.e., based on a paucity of growth strata; Pickering and Hilton, 1998; Sinclair and Tomasso, 2002; Tomasso and Sinclair, 2004); however, Pickering and Hilton (1998) interpreted that deformation increased seafloor gradients, which facilitated retrogressive sediment failure and sediment gravity-flow development.

2.4 OLIGOCENE-MIOCENE FOREDEEP-MARGIN AND WEDGE-TOP DEPOCENTERS, MOLASSE FORELAND BASIN SYSTEM, AUSTRIA

Tectonic loading of the southern margin of the European plate as a result of Alpine orogenesis induced subsidence and development of the Molasse foreland basin system during the late Eocene (Tollmann, 1978; Coward and Dietrich, 1989). Covault et al. (2008) characterized Oligocene-Miocene turbidite architecture across foredeep-margin and wedge-top depocenters of the Molasse foreland basin system and associated Eastern Alpine thrust front of Salzburg and Upper Austria (Figs. 2 and 7). Oligocene-Miocene turbidites compose the Puchkirchen turbidite complex (Rögl et al., 1979; Wagner, 1998), which includes an extensively studied, relatively large foredeep-axial channel belt (cf., De Ruig and Hubbard, 2006; Hubbard et al., 2008b) and less studied, small slope fans and piggyback-basin fills composing the foredeep-margin and wedge-top depozones, respectively (Covault et al., 2008; Fig. 7). Slope fans accumulated in pockets of accommodation (up to 6 km long, 3 km wide) created by canyon-channel systems and slump scars on the steep (locally as great as 20°), channelized foredeep-margin slope (De Ruig and Hubbard, 2006; Covault et al., 2008; Fig. 8). The steep gradient, however, is exaggerated principally by tectonic deformation that post-dates slope fan development, based on a paucity of growth strata (Covault et al., 2008; Fig. 8). Piggyback-basin fills accumulated in similarly small accommodation (up to 6 km long, 4 km wide) between thrust sheets of the Eastern Alpine thrust front (i.e., piggyback basins; Covault et al., 2008; Fig. 9). This wedge-top accommodation was created as a result of piggyback thrust propagation

(Dahlstrom, 1970; Butler, 1982; Ori and Friend, 1984; Covault et al., 2008; cf., the Eocene Ainsa piggyback basin discussed above; Fernández et al., 2004).

Slope fans are stacked up to 180 m thick, and include either amalgamated, relatively coarse-grained turbidite reservoirs with extrabasinal clasts (Haidach, Brunn, and Zagling fans; Figs. 7, 8, and 10), or texturally immature, intraformational mass transport-complex deposits (Astätt fan; Covault et al., 2008; Figs. 7 and 8). Coarse-grained slope fans are linked to tear faults that segment the Eastern Alpine thrust front (e.g., Haidach fan; Figs. 7 and 10). Tear faults provide a mechanism for transferring displacement between pairs of existing thrust faults (Dahlstrom, 1970). The tear faults likely facilitated the development of sediment conduits from hinterland source areas to pockets of accommodation across the steep foredeep-margin slope (Covault et al., 2008). Intraformational mass transport complex-dominated non-reservoir fans are not linked to tear faults, which might have inhibited sediment-conduit development, thereby preventing sediment gravity-flow transformations to coarse-grained turbidity currents (e.g., Astätt fan; Fig. 7). They were deposited as a result of slump/slide and debris-flow processes associated with the steep foredeep-margin slope (Covault et al., 2008).

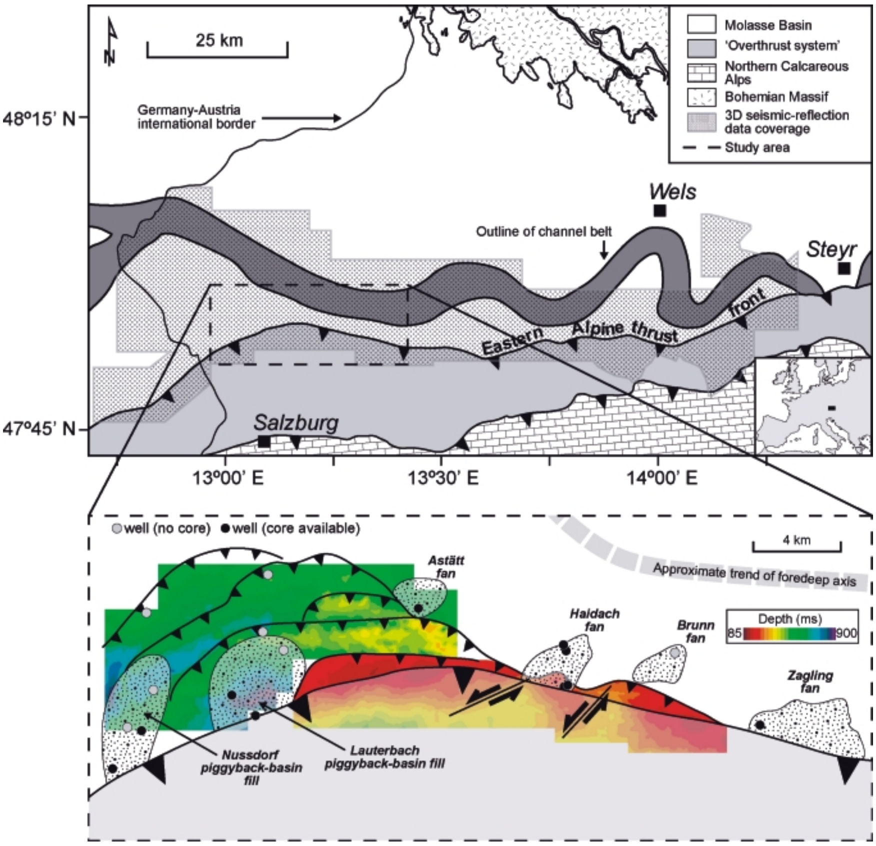

Figure 7: Location and structure maps of the Molasse foreland basin system. Above: Location map of the Molasse foreland basin system. Foredeep-axial channel belt of De Ruig and Hubbard (2006) and Hubbard et al. (2008b) outlined and shaded for context. Dashed black box represents location of structure map below. Black squares are cities. For information pertaining to the 'Overthrust system,' see Covault et al. (2008). Below: Wedge-top structure map. Colors represent depth (one-way travel time; ms). Turbidite systems are transparent white with a stippled pattern. Well locations identified by black (drill core available and described) and gray (no drill core available) circles. Modified from De Ruig and Hubbard (2006) and Covault et al. (2008).

Piggyback-basin fills in wedge-top accommodation exhibit turbidite systems up to 450 m thick, which pass from relatively fine-grained mass transport-complex deposits at the base of steep piggyback-basin margins to upward-fining and -thinning turbidites stratigraphically partitioned by mass transport-complex deposits across flat, unconfined basin floors (Covault et al., 2008; Fig. 11). Eastern Alpine thrust-front propagation likely promoted retrogressive sediment failure and sediment gravity-flow development in piggyback basins, and facilitated stratal thinning during progressive deformation (Covault et al., 2008).

2.5 COMMON ARCHITECTURAL CHARACTERISTICS AND TECTONIC/TOPOGRAPHIC INFLUENCES ON DEVELOPMENT

2.5.1 FOREDEEP-MARGIN DEPOCENTERS

Characteristics of foredeep-margin stratigraphic architecture from studies of the culmination of Miocene Marnoso-arenacea Formation deposition in the Apenninic foredeep and Oligocene-Miocene Puchkirchen Formation slope fan deposition in the Molasse foredeep are comparable (Ricci Lucchi, 1986; Covault et al., 2008). Both margins are characterized by erosional un-

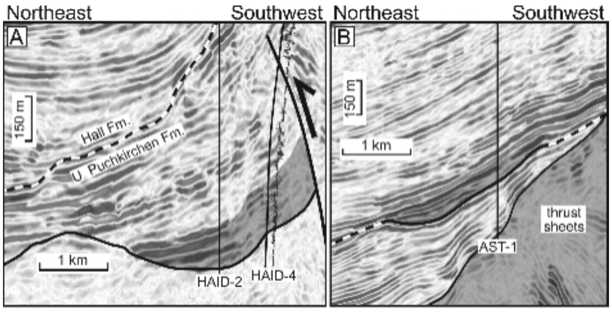

Figure 8: Molasse foredeep-margin slope-fan turbidite systems. (A) Seismic-reflection profile of Haidach fan highlighted with gray. Thrust fault truncates Haidach fan and is a structural trap. Vertical black lines are wells. Gamma ray wireline log is to the southwest of well HAID-4. (B) Seismic-reflection profile of Astätt fan highlighted with gray. The boundary between the Upper Puchkirchen and Hall formations is identified with black-and-white dashed lines. See Figure 7 for turbidite-system locations. Modified from De Ruig and Hubbard (2006) and Covault et al. (2008).

conformities and packages of turbidites up to hundreds of meters thick in pockets of slope accommodation created by canyon-channel systems and/or slump scars (Ricci Lucchi, 1986; De Ruig and Hubbard, 2006; Covault et al., 2008; Fig. 12). Turbidites also include relatively coarse-grained sand and gravel from distant hinterland source areas, and intraformational clasts are rare, but present (Ricci Lucchi, 1986; Covault et al., 2008; Fig. 12).

2.5.1.1 Tectonic deformation

Structures transverse or oblique to the Apenninic and Eastern Alpine thrust fronts facilitated the development of sediment conduits from hinterland source areas to pockets of accommodation across steep foredeep-margin slopes and axial foredeeps (Ricci Lucchi, 1986; Covault et al., 2008; Figs. 3, 4, 7, and 12). Transverse structures and topographic lows have been recognized as important sediment conduits associated with shallow- and non-marine depositional systems in many other foreland basin-system settings, including the Cenozoic Pyrenean foreland basin system (Hirst and Nichols, 1986; Coney et al., 1996; Vincent and Elliot, 1997), Cenozoic Himalayan foredeep (Burbank et al., 1986), and Cenozoic Venetian basin (Massari et al., 1986). Tectonic deformation also increased Apenninic and Molasse foredeep-margin gradients (Ricci Lucchi, 1986; Covault et al., 2008).

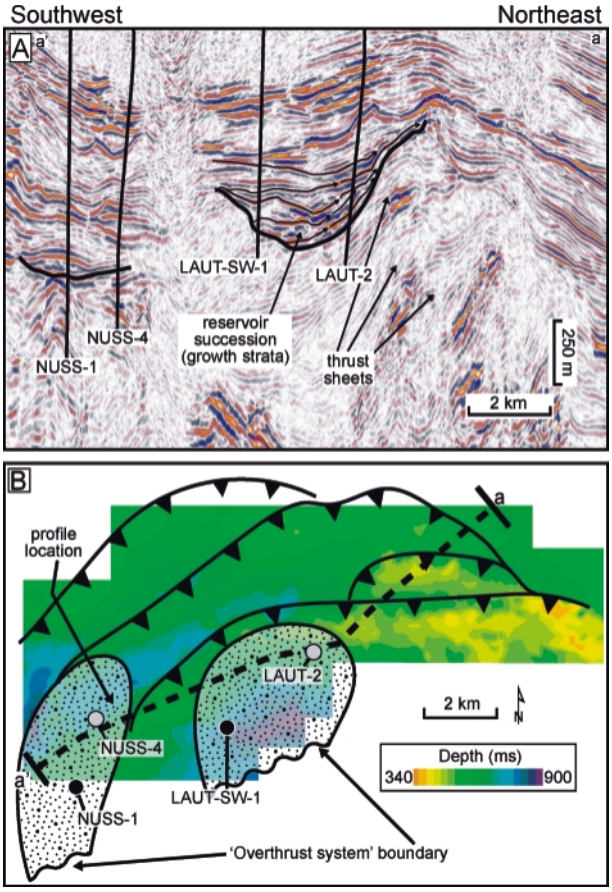

Figure 9: Molasse piggyback basin-fill turbidite systems. (A) Seismic-reflection profile of Nussdorf (left) and Lauterbach (right) systems. Piggyback-basin floors are discontinuous, curved, horizontal black lines (i.e., floors before they were covered with sediment). Growth strata are identified in the Lauterbach system by thin black lines. Arrows indicate the direction of stratal thinning (i.e., the direction of piggyback thrust propagation; Dahlstrom, 1970; Butler, 1982). Wells are vertical black lines. Seismic-reflection-profile location in B. (B) Structure map from Figure 7 with wells and seismic-reflection profile location. Modified from Covault et al. (2008).

2.5.1.2 Submarine topography

Submarine topography is also an important control on foredeep-margin stratigraphic architecture. Prevalence of erosional features across foredeep-margin slopes, including canyon-channel systems and slump scars, is a result of relatively steep gradients, which promote retrogressive sediment failure and sediment gravity-flow acceleration and accumulative flow behavior (Lowe, 1982; Kneller, 1995; McCaffrey and Kneller, 2004; Fig. 12). Tear fault-constrained (potentially extensive) channelization facilitates sorting of fluvial and sediment gravity-flow sediment to predominantly include coarse-grained sand during transit from subaerial hinterland source areas to deep-water sites of slope accommodation (i.e., channelization promotes turbidity-current run-out distance and grain-size fractionation/flow filtering; Lowe, 1982; Sylvester, 2001). Narrow and steep canyon-channel systems also thicken flows, which facilitates erosion of the underlying traction-structured tops of turbidites by turbidity currents (Kneller, 1995), thereby leading to the observed amalgamation of thick beds and paucity of traction structures in pockets of slope accommodation (cf., Molasse slope-fan reservoir architecture; Covault et al., 2008; Fig. 10). Local, relatively flat pockets of accommodation cause rapid deceleration, depletion, and consequent deposition of sediment gravity flows (Lowe, 1982; Kneller, 1995; McCaffrey and Kneller, 2004; Fig. 12).

The Astätt slope fan of the Molasse foredeep-margin slope is not linked to a tear fault-constrained canyon-channel system (Fig. 7), which inhibited sediment-conduit development, thereby preventing sediment gravity-flow transformations to coarse-grained turbidity currents (Lowe, 1982; Fisher, 1983; Covault et al., 2008). As a result, it is characterized by relatively fine-grained mass transport-complex deposits, which were deposited as a result of slump/slide and debris-flow processes associated with the steep foredeep-margin slope (Covault et al., 2008).

2.5.2 Wedge-top depocenters

Wedge-top stratigraphic architecture generally includes relatively fine-grained mass transport-complex deposits at the base of steep basin margins adjacent to thrust sheets and turbidites stratigraphically partitioned by mass transport-complex deposits across flat, unconfined basin floors (Ricci Lucchi, 1986; Mutti, 1992; Sinclair, 2000; Covault et al., 2008; Fig. 13). Turbidites are often organized into upward-fining and -thinning stratigraphic packages (Ricci Lucchi, 1986; Mutti, 1992; Covault et al., 2008; Fig. 13). Basin fill is typically on the order of hundreds of meters thick; however, it can approach kilometers in thickness (Ricci Lucchi, 1986; Mutti, 1992; Sinclair and Tomasso, 2002; Covault et al., 2008). Lateral stratigraphic thickness changes are dramatic (e.g., from >1000 m to <100 m across <5 km in Apenninic satellite basins; Ricci Lucchi, 1986) and growth strata are common (Ricci Lucchi, 1986; Fernández et al., 2004; Covault et al., 2008).

2.5.2.1 TECTONIC DEFORMATION

Syn-depositional fold-thrust belt development can create accommodation in which appreciable volumes of turbidites accumulate. Accommodation can develop as a result of syn-depositional vertical movements along structures perpendicular to the thrust front (cf., Apenninic satellite basins; Ricci Lucchi, 1986) and forward propagation of thrust sheets (cf., Apenninic satellite basins; Ricci Lucchi, 1986; Pyrenean piggyback basins; Mutti, 1985, 1992; Fernández et al., 2004; Pickering and Corregidor, 2005a, 2005b; and Molasse piggyback basins; Covault et al., 2008). Progressive deformation is reflected by growth strata, which create wedge-shaped turbidite-system architecture (cf., Apenninic satellite-basin fills; Ricci Lucchi, 1986; Ainsa basin-filling turbidite systems; Fernández et al., 2004; and Molasse piggyback-basin fills; Covault et al., 2008). When syn-depositional deformation is negligible with respect to wedge-top accommodation creation, inherited submarine topography from earlier fold-thrust belt development can control the location and geometry of basins (cf., the Annot basin; Pickering and Hilton, 1998; Sinclair and Tomasso, 2002).

Stacks of upward-fining and -thinning turbidite packages can be attributed to tectonically induced sediment failure and sediment gravity-flow development (Ricci Lucchi, 1986; Mutti, 1985, 1992; Pickering and Hilton, 1998; Pickering and Corregidor, 2005a, 2005b; Covault et al., 2008). Mutti (1992) noted that tectonic oversteepening can initiate retrogressive slumps and slides across steep basin margins, which transform into debris flows and turbidity currents downstream (Fisher, 1983; Fig. 14). The volume of sediment gravity flows likely decreases with time as the progressively flatter basin margin approaches an equilibrium profile, which creates an upward-fining and -thinning basin-fill succession (Mutti, 1992; Fig. 14). Sediment gravity-flow volumes can also progressively decrease if there is insufficient time for sediment accumulation/recharge in the shelf-edge staging area between episodes of tectonic deformation (Mutti, 1985). The Annot basin is filled with a distinctively different upward-coarsening and -thickening stratigraphic succession (Sinclair, 1994; Sinclair, 2000; Sinclair and Tomasso, 2002). This stratigraphic architecture reflects consistent basin filling and geometry relative to settings in which deformation and sedimentation are coeval (i.e., relative to settings in which sediment gravity-flow development is a result of episodic pulses of tectonic deformation, which leads to the deposition of upward-fining and -thinning stratigraphic packages as the basin margin approaches an equilibrium profile; Mutti, 1992; Sinclair and Tomasso, 2002; Fig. 14).

2.5.2.2 SUBMARINE TOPOGRAPHY

Wedge-top submarine topography influences the distribution of sedimentary facies. The lateral facies transition from relatively fine-grained mass transport-complex deposits to upward-fining and -thinning turbidites across basin floors reflects the intrabasinal transition from regions of relatively steep to flat topography (Ricci Lucchi, 1986; Mutti, 1992; Sinclair, 2000; Covault et al., 2008; Fig. 13). Slumping and sliding processes across steep basin margins, which lead to the deposition of chaotic mass transport-complex deposits at the break in slope,

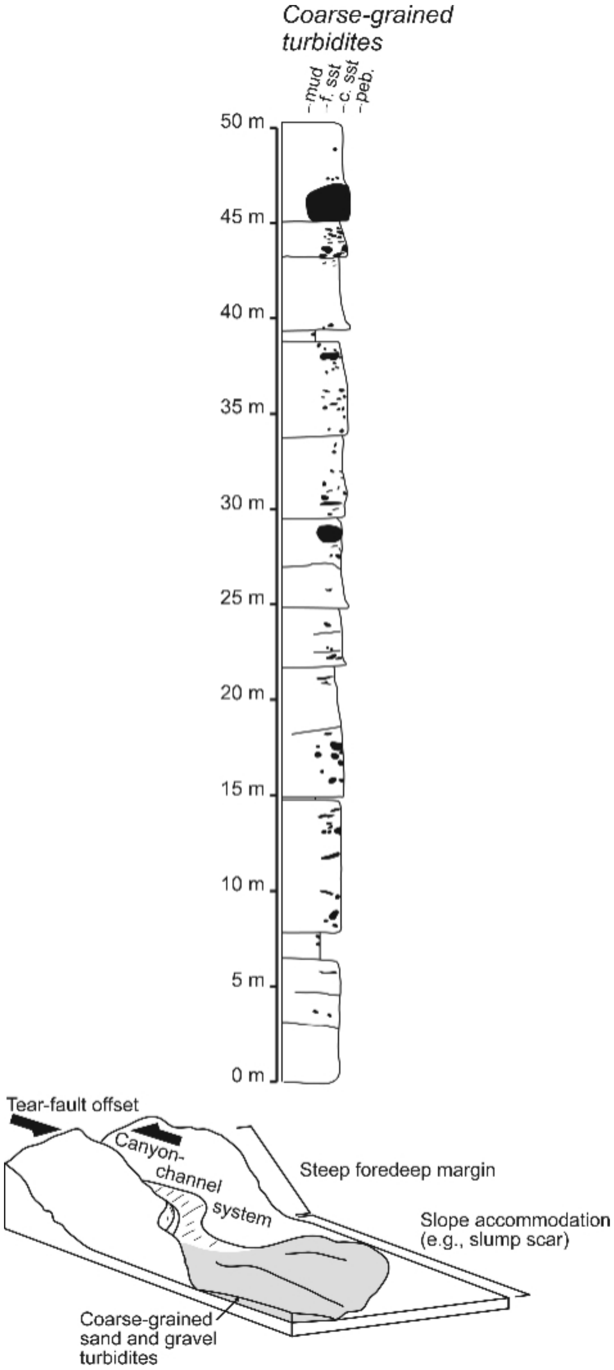

FIGURE 10: Molasse foredeep-margin slope-fan architecture. (Above) Generalized grain-size profile of amalgamated, thick-bedded turbidites. (Below) Summary diagram of Molasse foredeep-margin turbidite architecture. Tear fault offsetting a thrust front, and relatively coarse-grained turbidite-system development in foredeep-margin slope accommodation. Modified from Covault et al. (2008).

reflect highly unsteady, accumulative, followed by depletive flow behavior (e.g., immediately following sediment failure flows accelerate down the steep slope, followed by rapid deceleration and deposition at the break in slope; Lowe, 1982; Kneller, 1995; Walker et al., 1995; McCaffrey and Kneller, 2004; Fig. 13). Slumps and slides can transform into debris flows and turbidity currents downstream (Fisher, 1983), which deposit across the relatively flat, unconfined basin floor (Lowe, 1982; Kneller, 1995; McCaffrey and Kneller, 2004; Fig. 13). Progressively changing submarine topography during Annot basin filling is reflected by upward-coarsening and -thickening stratigraphic successions. Accommodation was progressively destroyed as a result of Annot basin filling and, as a result, submarine topography became progressively steeper (i.e., indicated by interpretations of phases of sediment gravity-flow ponding, followed by flow stripping, and culminating with bypass; Sinclair and Tomasso, 2002).

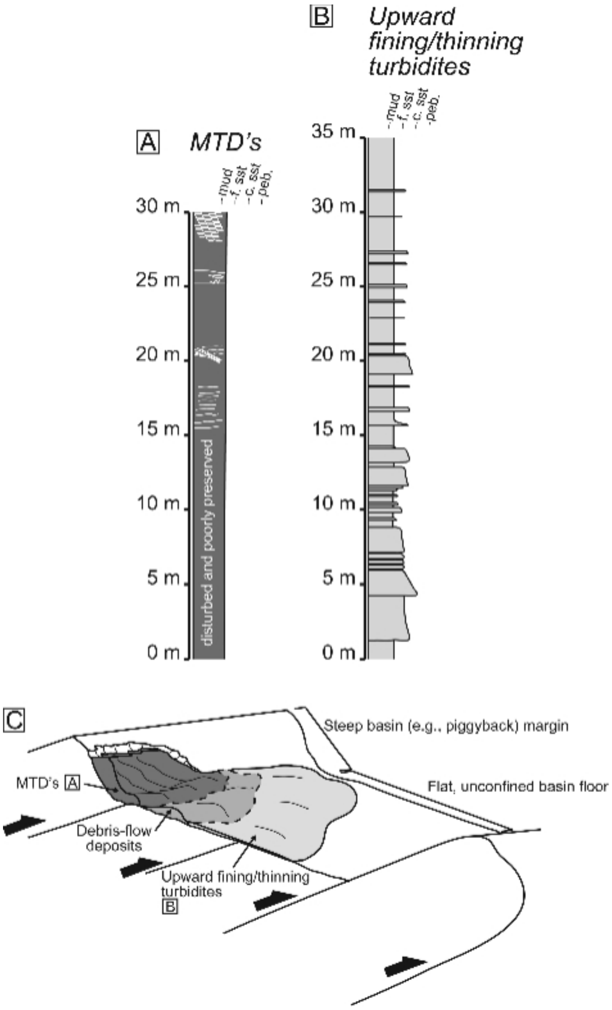

Figure 11: Molasse piggyback basin-fill architecture. (A) Generalized grain-size profile of chaotic mass transport-complex deposits (MTD's). (B) Generalized grain-size profile of upward-fining and –thinning turbidites. (C) Summary diagram of Molasse piggyback basin-fill architecture. Sediment failure-induced slumps/slides and debris-flow deposits along basin margins pass to turbidites across flat basin floors. Modified from Covault et al. (2008).

3. Comparison to the passive-margin Gulf of Mexico slope

Reservoir models derived from studies of Neogene Gulf of Mexico salt-withdrawal basins (e.g., Satterfield and Beherens, 1990; Prather et al., 1998; and Beaubouef and Friedmann, 2000) have been widely cited in studies of structurally complex slope depocenters. For example, Gulf of Mexico models have been recently cited in studies of the Cretaceous Inner Moray Firth rift sub-basin of the North Sea (Argent et al., 2000); the Cenozoic French Alpine foreland basin (Sinclair, 2000; Sinclair and Tomasso, 2002); the Paleozoic Karoo foreland basin, South Africa (Grecula et al., 2003); a Quaternary trench-slope basin in the Nankai subduction zone of southwest Japan (Underwood et al., 2003); Cenozoic shale-diapir basins of the Niger Delta slope offshore Nigeria (Adeogba et al., 2005); the Cretaceous-Cenozoic Magallanes foreland basin, Chile (Shultz and Hubbard, 2005); the Cretaceous-Cenozoic northern Santa Lucia strike-slip basin, California (Anderson et al., 2006); the Cenozoic Molasse foreland basin (De Ruig and Hubbard, 2006); and Quaternary salt-withdrawal basins offshore Angola (Gee et al., 2007). As discussed in the introduction, significant differences in tectonic deformation and submarine topography between depocenters in different settings foster the development of distinctively different reservoir architectures. Therefore, widely-used models of turbidite-reservoir development in Gulf of Mexico salt-withdrawal basins are unlikely to accurately predict reservoir quality in tectonically and topographically disparate proximal foreland basin-system depocenters.

3.1 Tectonic deformation

The primary difference in tectonic deformation between Gulf of Mexico salt-withdrawal basins and foreland basin systems is the driving mechanism behind deformation (Rowan et al., 2004). In the Gulf of Mexico, deformation is predominantly driven by rapid and voluminous sedimentation and consequent gravitational instability (Fails, 1990; Diegel et al., 1995; Rowan et al., 2004). Booth et al. (2000) and Twichell et al. (2000) presented comparable depositional models for Gulf of Mexico turbidite-reservoir architecture that accounted for the interplay of sediment supply and salt tectonics (Fig. 15). During periods of significant turbidite deposition, the rate of sediment supply overwhelms the rate of subsidence related to salt tectonics and, as a result, basins are filled with turbidites (Booth et al., 2000; t=1 and t=2 of Fig. 15). During periods of reduced sediment supply, the rate of basin subsidence (which is partly driven by the load of the previously deposited turbidites) exceeds the rate of sedimentation and, as a result, accommodation is renewed in basins (Booth et al., 2000; t=3 of Fig. 15). High-frequency (i.e., several thousands to tens of thousands of years) perturbations in the rate of sediment supply allow basin accommodation to renew at a rate sufficient to allow deposition and preservation of isopachous packages of coarse-grained turbidite sandstone or sand stratigraphically partitioned by fine-

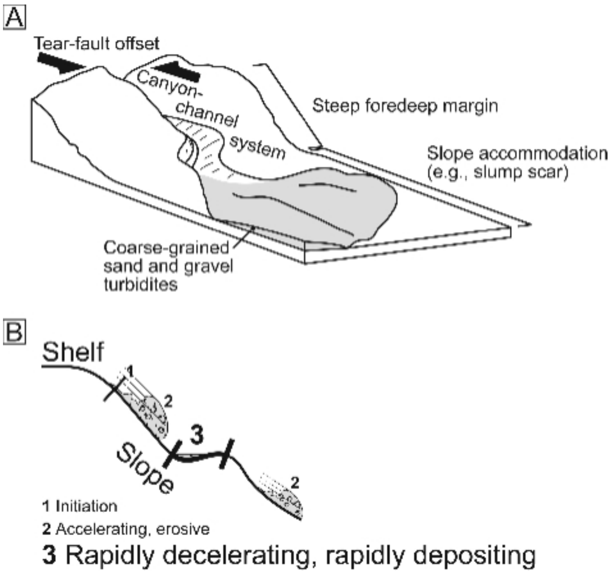

Figure 12: Summary diagrams of foredeep-margin turbidite architecture and sediment gravity-flow behavior. (A) Tear fault offsetting a thrust front, and relatively coarse-grained turbidite-system development in foredeep-margin slope accommodation. Modified from Covault et al. (2008). (B) Generalized diagram of downslope changes in sediment gravity-flow behavior. Topographic zones are numbered. Topographic zone 3 is a local, flat pocket of accommodation, which causes rapid deceleration, depletion, and consequent deposition of sediment gravity flows. Enlarged text refers to topographic zone 3, where sediment gravity-flow deposition occurs.

grained mass transport-complex and hemipelagic deposits (Booth et al., 2000; Fig. 15); however, stratigraphic packages might include growth strata that subtly thin onto basin margins against salt diapirs (Lopez, 1990).

In proximal foreland basin systems and associated fold-thrust belts, deformation is externally driven by lithospheric plate movements, not by gravitational instability (which is typically the case in passive-margin settings such as the Neogene Gulf of Mexico; Rowan et al., 2004). Consequently, foreland basin-system deformation is more resistant to slight, short-term (i.e., several thousands to tens of thousands of years) increases in overburden thickness and strength (i.e., sedimentation patterns) relative to gravity-driven passive margin settings (although, foreland basin-system accommodation creation is partially attributed to longer-term accumulation of voluminous foredeep sedimentary loads; DeCelles and Giles, 1996; Rowan et al., 2004).

Foredeep margins are commonly segmented by oblique-to-thrust-front-oriented structures (cf., Burbank et al., 1986; Hirst and Nichols, 1986; Homewood et al., 1986; Massari et al., 1986; Ori et al., 1986; Ricci Lucchi, 1986; Coney et al., 1996; Vincent and Elliott, 1997; DeCelles and Giles, 1996; Covault et al., 2008). These structures can facilitate the development of sediment conduits from hinterland source areas to pockets of accommodation across steep foredeep-margin slopes and axial foredeeps (Ricci Lucchi, 1986; Covault et al., 2008). Turbidite fill in the slope pockets are amalgamated and relatively coarse-grained (Ricci Lucchi, 1986; Covault et al., 2008), which is distinctively different from salt-withdrawal basin fill (cf., Beaubouef and Friedmann, 2000; Booth et al., 2000; Mallarino et al., 2006).

Wedge-top depocenters are commonly influenced by syndepositional deformation, which is reflected by growth strata. Slight, short-term sedimentation patterns have a negligible influence on deformation; rather, sedimentation synchronous with deformation can facilitate the development of more tapered turbidite-reservoir architecture (in contrast to isopachous Gulf of Mexico salt-withdrawal basin fill; Ricci Lucchi, 1986; Covault et al., 2008; Fig. 15). Deformation also plays an important role in sediment failure and sediment gravity-flow development, and the consequent deposition of stacks of upward-fining and -thinning turbidite packages (Mutti, 1992; Fig. 14).

3.2 SUBMARINE TOPOGRAPHY

Gulf of Mexico salt-withdrawal basins have distinctively different topography relative to proximal foreland basin-system depocenters. The regional Gulf of Mexico slope is relatively flat (<1°; Prather et al., 1998) and pock-marked with circular saltwithdrawal basins, which are typically less than 20 km in diameter with margins with relief rarely exceeding 200 m (Beaubouef and Friedmann, 2000; Mallarino et al., 2006). This topography facilitated the development of sinuous channel-levee systems across the regionally flat slope (Flood and Damuth, 1987; Mutti et al., 2003). Salt-withdrawal basin fill includes hundreds-of-meters-thick isopachous packages of coarse-grained turbidite sandstone or sand stratigraphically partitioned by fine-grained mass transport-complex and hemipelagic deposits (Beaubouef and Friedmann, 2000; Booth et al., 2000; Mallarino

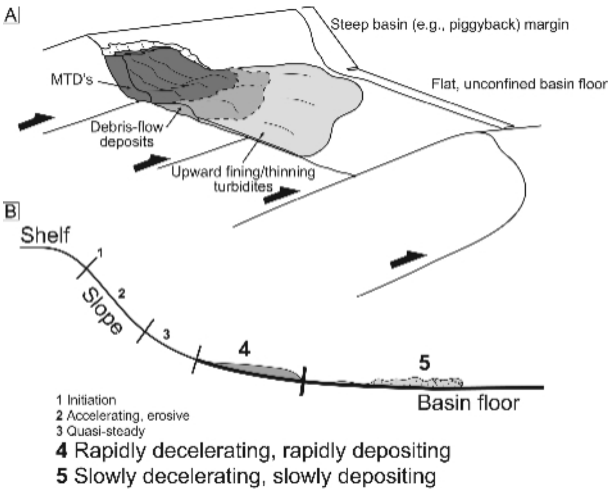

Figure 13: Summary diagrams of wedge-top turbidite architecture and sediment gravity-flow behavior. (A) Piggyback-basin margin and floor, and the transition from sediment failure-induced slumps/slides and debris-flow deposits along basin margins to turbidites across flat basin floors. Modified from Covault et al. (2008). (B) Generalized diagram of downslope changes in sediment gravity-flow behavior. Topographic zone 4 is the base of the steep basin-margin slope, which causes rapid deceleration, depletion, and consequent deposition of slumped and slid sediment. Slumps and slides can transform into debris flows and turbidity currents downstream, and deposit across topographic zone 5, which is the flat, unconfined basin floor. Enlarged text refers to topographic zones 4 and 5, where sediment gravity-flow deposition occurs.

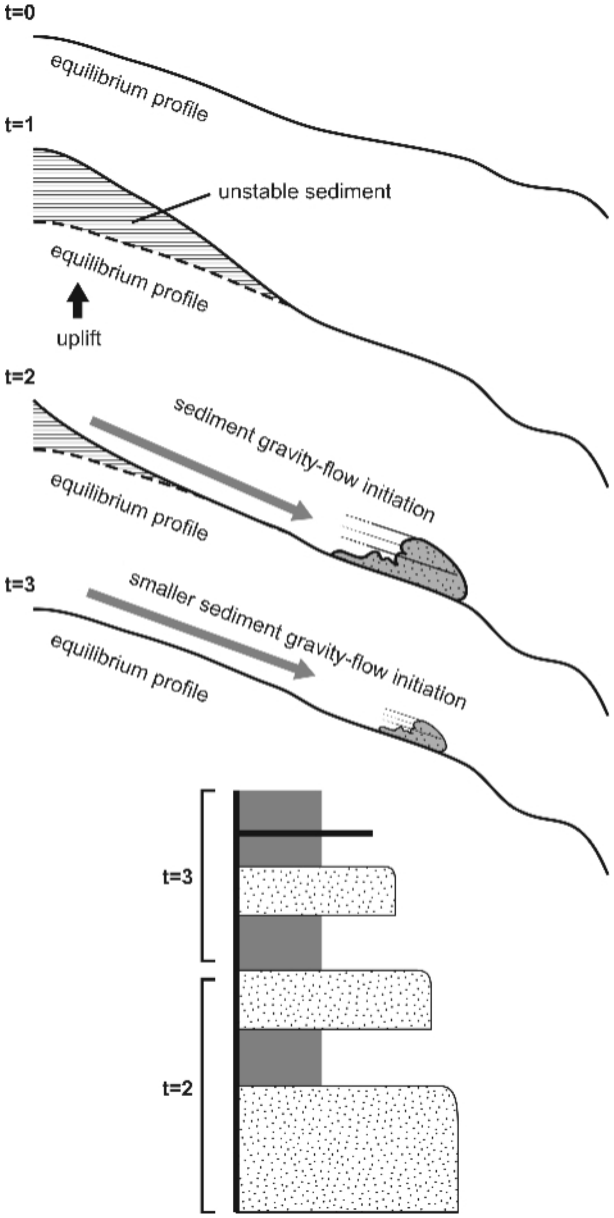

Figure 14: Schematized relationship between tectonic overstepening and basin-floor upward-fining and -thinning facies sequences. t=0 is prior to uplift when the equilibrium profile is established. t=1 is following uplift. t=2 is following initial, voluminous retrogressive sediment failure. t=3 is following subsequent, less voluminous sediment failure, when the equilibrium profile is reestablished. Modified from Mutti (1992).

et al., 2006), which represents a multiphase development comparable to Annot basin filling (i.e., stacked turbidite packages represent phases of sediment gravity-flow ponding, followed by flow stripping, and culminating with bypass; Sinclair and Tomasso, 2002; Fig. 6).

Proximal foreland basin-system depocenters are significantly steeper (cf., Molasse foredeep-margin and wedge-top gradients; Covault et al., 2008), and pockets of accommodation across steep foredeep margins are distinctively smaller than Gulf of Mexico salt-withdrawal basins (e.g., Molasse foredeep-margin slope fans are <6 km long and <3 km wide; Covault et al., 2008). Steep foredeep-margin gradients and relatively straight, tear fault-constrained canyon-channel systems facilitate deposition of amalgamated and coarse-grained turbidite reservoirs (Ricci Lucchi, 1986; Covault et al., 2008; Fig. 12). This architecture is distinctively different from salt-withdrawal basin fill (cf., Beaubouef and Friedmann, 2000; Booth et al., 2000; Mallarino et al., 2006). In some cases, wedge-top basins exhibit similar geometries and topographies relative to salt-withdrawal basins (i.e., they are steep sided, flat floored, and less than 20 km in diameter; e.g., Apenninic satellite basins; Ricci Lucchi, 1986; the Annot basin; Sinclair and Tomasso, 2002; and Molasse piggyback basins; Covault et al., 2008), and, as a result, basin fills share similar facies characteristics (i.e., they include relatively coarse-grained turbidites stratigraphically partitioned by mass transport-complex deposits; Sinclair and Tomasso, 2002; Fig. 13). However, for reasons discussed above, differences in tectonic setting between Gulf of Mexico salt-withdrawal basins and wedge-top depocenters facilitate the development of different reservoir architectures (e.g., wedge-top sedimentary fill often includes growth strata).

4. SEISMIC-REFLECTION-BASED EXPLORATION STRATEGY

Common tectonic and topographic influences inherent to Cenozoic European proximal foreland basin-system depocenters facilitated the development of common architectural characteristics of turbidite systems and associated reservoirs. Therefore, interpretation of tectonic deformation and paleotopography in analogous structurally complex frontier areas is of paramount importance in assessing turbidite-reservoir distribution and quality. Provided extensive 3D seismic-reflection-data coverage, the fundamental step in turbidite-reservoir exploration should include detailed mapping of fold-thrust-belt structure. This will lead to the identification of accommodation between thrust sheets (cf., Molasse piggyback basins; Covault et al., 2008) and transverse structures and topographic lows, which localize sediment accumulation (cf., structures transverse to the Apenninic and Eastern Alpine thrust fronts; Ricci Lucchi, 1986; Covault et al., 2008). Structure maps should also be used in order to approximate paleotopography. As discussed above, zones of steep and/or confined topography facilitate flow acceleration and accumulative flow behavior, whereas zones of flat and unconfined topography facilitate deceleration and depletion (Lowe, 1982; Kneller, 1995; McCaffrey and Kneller, 2004; Figs. 12 and 13). For example, steep foredeep-margin gradients and confinement associated with canyon-channel systems facilitate sediment gravity-flow run-out distance (i.e., bypass) and grain-size fractionation (Lowe, 1982; Sylvester, 2001), whereas local, relatively flat pockets of accommodation cause rapid deposition of sediment gravity flows (Lowe, 1982; Kneller, 1995; McCaffrey and Kneller, 2004; Fig. 12).

The next step should include recognition (on the basis of seismic-reflection characteristics; cf., Covault et al., 2008) and mapping of turbidite systems in zones of accommodation between thrust sheets (e.g., piggyback-basin fills in Molasse wedge-top depocenters; Covault et al., 2008) and in local pockets across the steep slope forward of the fold-thrust belt (e.g., slope fans in canyon-channel systems and slump scars of the Apenninic and Molasse foredeep-margin slopes; Ricci Lucchi, 1986; Covault et al., 2008). Relatively few studies detail the seismic-reflection characteristics of proximal foreland basin-system turbidites and, as a consequence, insight from a large number of studies of relatively dissimilar passive margins is commonly applied (Mutti et al., 2003). Recent work of De Ruig and Hubbard (2006), and Covault et al. (2008), however, present seismic-reflection characteristics of slope fans and piggyback-basin fills in Molasse foredeep-margin and wedge-top depocenters.

The final step should be to compare tectonic features (e.g., piggyback accommodation, tear faults, etc.) and paleotopography to turbidite systems in order to assess reservoir distribution and quality. For example, a depositional body in local foredeep-margin slope accommodation, linked to a tear-fault-constrained canyon-channel system, likely comprises an amalgamated and coarse-grained turbidite reservoir (Ricci Lucchi, 1986; Covault et al., 2008; Fig. 12). Also, syn-depositional deformation in wedge-top depocenters facilitates sediment gravity-flow initiation and the development of a lateral facies transition from relatively fine-grained mass transport-complex deposits at the base of steep slopes to upward-fining and -thinning turbidite reservoirs across flat, unconfined basin floors (cf., Ricci Lucchi, 1986; Mutti, 1992; Sinclair, 2000; Covault et al., 2008; Fig. 13).

5. SUMMARY

In this review of European proximal foreland basin-system depocenters, we highlight common turbidite-system and associated reservoir architectural characteristics and developmental controls. Foredeep margins are characterized by erosional unconformities and packages of turbidites up to hundreds of meters thick in pockets of slope accommodation created by canyon-channel systems and/or slump scars. Wedge-top stratigraphic architecture generally includes relatively fine-grained mass transport-complex deposits at the base of steep basin margins adjacent to thrust sheets and turbidites stratigraphically partitioned by mass transport-complex deposits across flat, unconfined basin floors. Tectonic deformation and submarine topography are important influences on turbidite-reservoir distribution and quality. Oblique-to-thrust-front-oriented structures facilitate the development of sediment conduits from hinterland source areas to pockets of accommodation across steep foredeep-margin slopes and axial foredeeps. Syn-depositional fold-thrust belt development can create wedge-top accommodation in which appreciable volumes of turbidites accumulate. Syn-depositional deformation also creates wedge-shaped turbidite-reservoir architecture (i.e., growth strata) and initiates sediment failure. Submarine topography controls sediment gravity-flow behavior by promoting bypass or localizing sediment deposition. Widely used models of turbidite-reservoir development in Gulf of Mexico salt-withdrawal basins do not accurately predict reservoir quality in tectonically and topographically dissimilar proximal foreland basin-system depocenters. Insights from European proximal foreland basin-system depocenters suggest that the fundamental step in turbidite-reservoir exploration in analogous frontier areas should include detailed mapping of fold-thrust-belt structure. Structure maps facilitate identification of accommodation between thrust sheets, potentially extensive sediment conduits from hinterland source areas, and paleotopography.

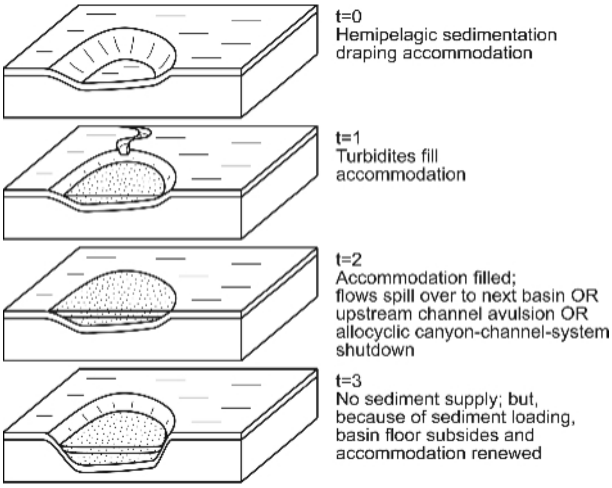

FIGURE 15: General depositional model for Neogene Gulf of Mexico turbidite-reservoir architecture that accounts for the interplay of sediment supply and salt tectonics. Modified from Twichell et al. (2000).

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Jacob A. COVAULT[*)] & Stephan A. GRAHAM
Department of Geological and Environmental Sciences, Stanford University, Stanford, CA, 94305-2115 USA
[*)] Corresponding author, jcovault@stanford.edu

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