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Growth patterns of deep-sea fans revisited: Turbidite-system morphology in confined basins, examples from the California Borderland

Jacob A. Covault *, Brian W. Romans [1]

Chevron Energy Technology Company, Clastic Stratigraphy R&D, San Ramon, CA 94583, USA

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A B S T R A C T

This study characterizes growth and morphologies of turbidite systems in confined receiving basins of the California Borderland. Morphologies were quantified according to volume, area, maximum thickness, length, and width using an extensive grid of seismic-reflection data. Turbidite systems that were supplied sufficient sediment to be confined by their basin margins were unable to areally expand and, as a result, subsequent turbidite deposition thickened the systems. Conversely, insufficient volumes of sediment to extend systems to their receiving-basin margins resulted in thinner systems. Turbidite systems exhibit progressively smaller maximum thickness-to-area ratios, i.e., system areas increased more than maximum thicknesses during successive growth phases. This is most likely a result of progressive turbidite deposition “healing” relatively high-relief bathymetry. We compared these examples from the California Borderland and a similar setting to larger, unconfined systems. The growth and morphologies of turbidite systems in confined receiving basins, such as the western Gulf of Mexico slope, are greatly influenced by relatively meager volumes of sediment supplied and receiving-basin confinement, and are distinctively different from larger systems in unconfined ocean basins with sediment supplied from extensive terrestrial drainages. Areal characteristics (i.e., length-to-width and length-to-area ratios) of turbidite systems are generally similar as a result of sediment-gravity-flow processes and larger-scale autogenic behavior (e.g., channel avulsion, lobe switching, etc.); however, differences are common in tectonically complex settings as a result of receiving-basin geometry. Results of this study provide insights into the distribution and morphology of the largest detrital accumulations on Earth, which can be directly applied to predictive models of turbidite-architecture development in confined receiving basins.

1. Introduction

Turbidite systems are the largest sediment accumulations in the deep sea, and turbidite reservoirs are the focus of significant exploration projects for hydrocarbon resources (Pettingill and Weimer, 2002). They are composed of sediment-gravity-flow deposits that record a series of genetically related erosional and depositional events that occurred in virtual stratigraphic continuity (Mutti and Normark, 1987). Turbidite systems primarily occur as submarine fans (Weimer and Link, 1991), which have well-developed channel-(levee)–overbank elements (Nelson et al., 1978; Bouma et al., 1985a), and include relatively unconfined lobes (or splays) at the distal ends of channels and on the overbank region where channel levees are breached (Normark et al., 1993; Posamentier and Kolla, 2003; Fildani and Normark, 2004).

Normark (1970) presented the first widely used model of submarine-fan growth from the California Borderland and offshore Baja California, which inspired subsequent studies regarding the development of modern and ancient turbidite systems (e.g., Mutti and Ricci Lucchi, 1972; Mutti, 1977; Nilsen, 1977; Walker, 1978; Normark, 1978; Normark et al., 1979; Normark and Hess, 1980; Nilsen, 1980; Nardin, 1983; Mutti, 1985; Mutti and Normark, 1991; Fildani and Normark, 2004). Modern refers to deposits whose geometry and surface morphology reflect original growth conditions, whereas ancient systems commonly include outcropping turbidites or subsurface systems that were subjected to post-depositional deformation (Mutti and Normark, 1991). Normark's (1970) seminal work introduced the turbidite-system growth-pattern concept, which was defined as the overall system morphology related to the origin and recent history of canyons and channels on the present seafloor.

Our work revisits the California Borderland and Normark's (1970) growth-pattern model (Figs. 1 and 2). We are less concerned with relatively fine-scale geomorphology and internal architecture of turbidite systems (cf., Normark, 1970; and studies of elements within turbidite systems, including Pickering et al., 1995; Weimer et al., 2000; Piper and Normark, 2001; Normark et al., 2002; Gervais et al., 2006; Deptuck et al., 2008; and Jegou et al., 2008). Rather, our work is primarily concerned with the evolution of and controls on turbidite-system morphology in entire basin-fill successions of turbidites (i.e., complexes; Mutti and Normark, 1987). In the context of this research, turbidite-

* Corresponding author. Tel.: +1 9258424218; fax: +1 9258422076.
E-mail addresses: jcovault@chevron.com (J.A. Covault), brian.romans@chevron.com (B.W. Romans)
[1] Tel.: +1 9258420379.

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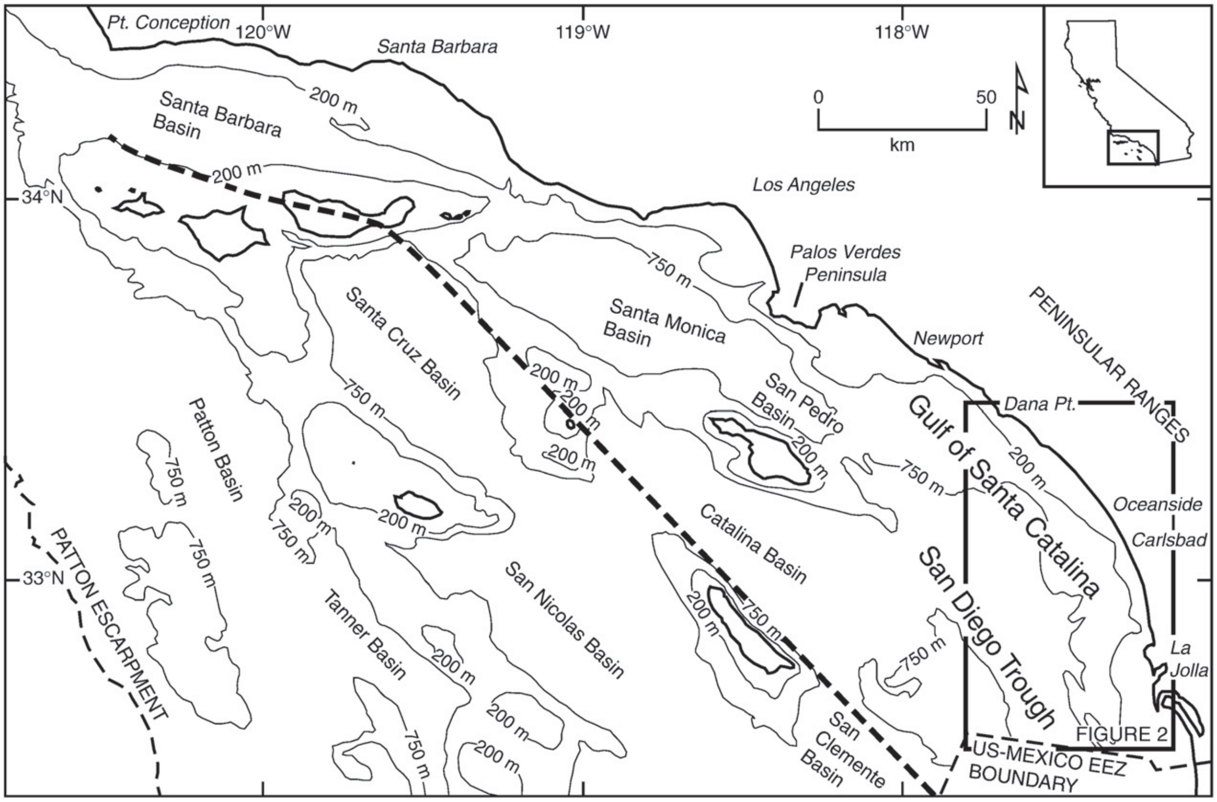


Fig. 1. Bathymetric map of the California Borderland (modified from Vedder, 1987). Dashed bold black line is the boundary between the inner and outer Borderland (Teng and Gorsline, 1991). Location of study area in Fig. 2 is boxed in the southeast corner.

system growth pattern refers to the overall system morphology related to the caliber and total volume of sediment supplied and receiving-basin geometry (following work of Nelson and Kulm, 1973; Pickering, 1982; Kolla and Coumes, 1987; Normark, 1985; Stow et al., 1985; Mutti and Normark, 1987; Kolla and Macurda, 1988; Shanmugam and Moiola, 1988; Wetzel, 1993; Apps et al., 1994; Reading and Richards, 1994; Prather et al., 1998; Booth et al., 2000; and Piper and Normark, 2001; to name a few). Turbidite systems with short-lived, sand-rich sediment sources that form in relatively confined basins likely develop distinctively different morphologies relative to longer-lived, finer-grained systems in large, unconfined ocean basins (Mutti and Normark, 1987).

We quantify the morphologies of the entire turbidite systems in the California Borderland according to volume, area, maximum thickness, length, and width. Borderland turbidite-system morphologies are compared to systems in confined salt-withdrawal basins of the western Gulf of Mexico and larger systems in unconfined ocean basins with sediment supplied from extensive terrestrial drainages. Results provide insights into the distribution and morphology of the largest detrital accumulations on Earth, which can be directly applied to predictive models of large-scale turbidite-architecture development in confined settings.

2. Regional setting

2.1. The California Borderland

The California Borderland is the region offshore southern California characterized by a relatively narrow shelf and complex basin-and-ridge bathymetry (Shepard and Emery, 1941) (Figs. 1 and 2). It extends south from Point Conception, offshore the United States, to Bahia Sebatian Vizcaino and Cedros Island, Mexico (Vedder, 1987) (Fig. 1). The Patton Escarpment is the seaward boundary of the California Borderland, which is underlain by a subduction complex associated with the Mesozoic to Paleogene Great Valley forearc basin (Crouch, 1979, 1981; Teng and Gorsline, 1991). Crouch (1979, 1981) divided the California Borderland into inner and outer regions according to the distribution of pre-Neogene basement rocks, which are lithologically and structurally correlatable with the Franciscan subduction complex and Great Valley forearc-basin sequence of central and northern California (Crouch, 1979, 1981) (Fig. 1).

The development of the California Borderland began during the Miocene, when subduction associated with the Great Valley forearc basin had ceased and transform tectonism dominated the region (Crouch, 1979, 1981; Yeats and Haq, 1981). Oblique divergence between the Pacific and North American plates resulted in large-scale extension and strike-slip faulting (Lonsdale, 1991), which facilitated significant deformation of the continental margin, including folding and faulting of basinal sediment, uplift of deep-seated basement rocks, and extensive volcanism (Crouch, 1981; Teng and Gorsline, 1991). In the late Miocene, transform tectonism was focused inland at the location of the present San Andreas Fault zone (Crowell, 1979, 1981), and moderate strike-slip fault-related deformation created the present basin-and-ridge bathymetry of the California Borderland (Teng and Gorsline, 1991).

This study focuses on turbidite-system growth in two inner basins of the southern California Borderland, the southeastern Gulf of Santa Catalina and, to a lesser extent, the seaward San Diego Trough (Figs. 1 and 2). The informal boundary between the northern and southern California Borderland is the Palos Verdes Peninsula (Fig. 1). The southeastern Gulf of Santa Catalina and San Diego Trough are elliptical basins, each up to 80 km long and 25 km wide, and trend approximately northwest–southeast (Fig. 2). They are separated by a series of fault-bounded bathymetric highs, including, from north to south, Crespi Knoll, Carlsbad ridge, and Coronado Bank (Fig. 2). The southeastern Gulf of Santa Catalina is filled to its bounding ridges and, as a result, late Pleistocene–Holocene turbiditic sediment spills into the seaward San Diego Trough.

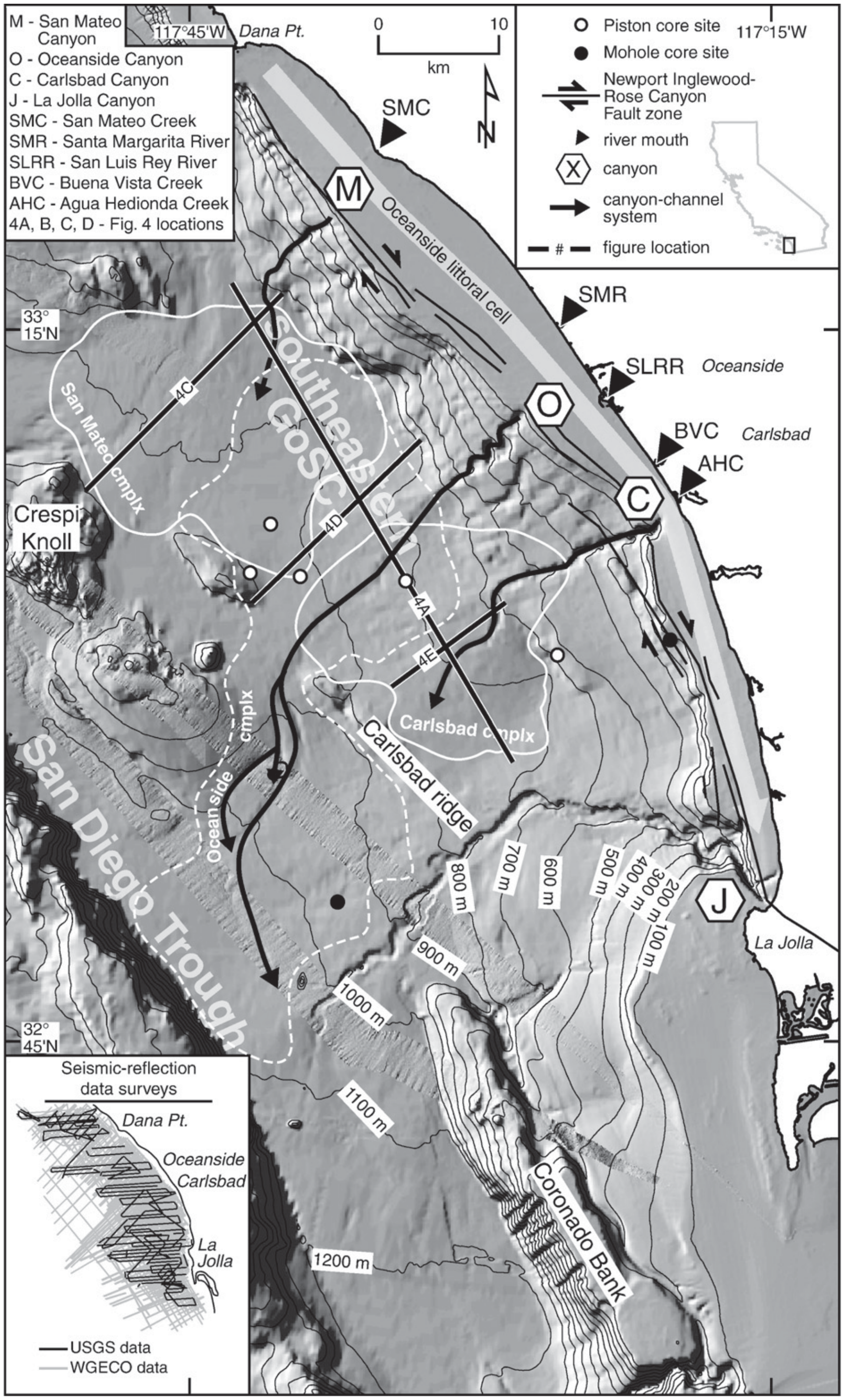


Fig. 2. Multibeam bathymetric map of the inner southern California Borderland, including the southeastern Gulf of Santa Catalina (GoSC) and San Diego Trough and turbidite complexes therein (outlined in white lines; Oceanside complex is dashed in order to differentiate between other complex boundaries). Lower left: Geophysical survey tracklines from Normark et al. (1999), Gutmacher et al. (2000), Sliter et al. (2005), and the National Archive of Marine Seismic Surveys (U.S. Geological Survey, 2006). Bathymetry courtesy of Peter Dartnell (Gardner and Dartnell, 2002; Dartnell et al., 2007). Mohole drill-core and U.S. Geological Survey piston-core locations from Inman and Goldberg (1963) and U.S. Geological Survey (1999, 2003).

2.2. Late Pleistocene–Holocene staging area to the southeastern Gulf of Santa Catalina

Three canyon-and-channel systems supplied sediment to the southeastern Gulf of Santa Catalina. These are, from north to south, the San Mateo, Oceanside, and Carlsbad canyon-and-channel systems (Fig. 2). These systems are submarine sediment conduits that pass from V-shaped canyons at the shelf edge and uppermost slope to U-shaped channels with overbank elements across the lower slope and basin floor. Their canyon heads are located at relatively wide segments of the shelf (i.e., shelf widths from the San Mateo, Oceanside, and Carlsbad canyon heads to the present shoreline are approximately 7 km, 6 km, and 2 km,

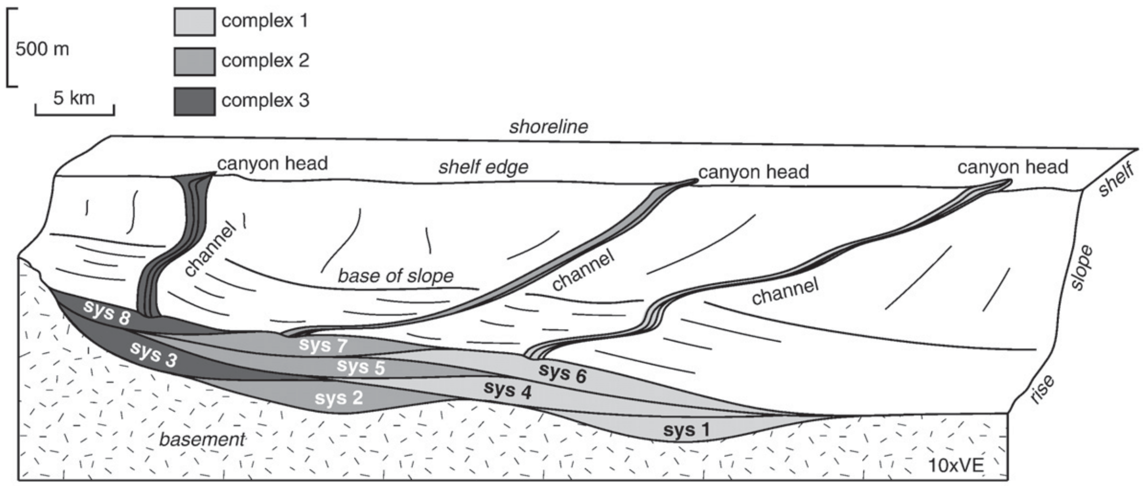


Fig. 3. Schematic modern turbidite systems (labeled 'sys #' according to sequence of growth phases) and complexes (shaded) based on Quaternary turbidite depositional units in the California Borderland of this study (cf., Fig. 4A). Turbidite systems (labeled 'sys #') are commonly hundreds of meters thick, lenticular in cross section, and conform to receiving-basin geometry in plan view. Modern turbidite systems that were fed sediment from canyons and channels during multiple growth phases are stacked one upon the other and form composite bodies, which are turbidite complexes (shaded; Mutti and Normark, 1987).

respectively, which are large relative to the highstand-active La Jolla Canyon head that has been incised across the shelf nearly to the present shoreline; Covault et al., 2007) (Fig. 2). The southern California Borderland shelf edge is bounded by the Newport Inglewood-Rose Canyon fault zone, and has remained relatively fixed as a result of late Pleistocene–Holocene fault movement (Fischer and Mills, 1991) (Fig. 2). During late Pleistocene intervals of low sea level, canyon heads received terrigenous sediment from segments of the paleo-Oceanside littoral cell and rivers that were able to extend across the subaerially exposed shelf (Covault et al., 2007) (Fig. 2). Small rivers drain steep terrain of the Peninsular Ranges, which are composed of Jurassic and Cretaceous plutonic rocks overlain by a veneer of Tertiary and Quaternary sediment and sedimentary rocks (Inman and Jenkins, 1999; Warrick and Farnsworth, 2009). Canyon heads are stranded at the outer shelf as a result of late Pleistocene–Holocene sea-level rise (i.e., since 20 ka; Lambeck and Chappell, 2001) and, as a result, canyons and channels are inactive today (Covault et al., 2007).

3. Data and methods

Turbidite systems and larger-scale complexes were recognized and mapped in two-dimensional seismic-reflection profiles from Western Geco multichannel geophysical surveys (W-3-75-SC, W-30-81-SC, W-31-81-SC, W-5-82-SC, and W-7-85-SC; U.S. Geological Survey, 2006), and U.S. Geological Survey multichannel and Huntec deep-tow boomer geophysical surveys (O-1-99-SC and A-1-03-SC; Normark et al., 1999; Gutmacher et al., 2000; Sliter et al., 2005) (Fig. 2). Depth values through late Pleistocene–Holocene sediment were converted from two-way travel time (ms) to meters based on a compressional sound velocity of 1600 m/s (Hamilton et al., 1956; Covault et al., 2007). The likely minor effects of sediment compaction are negligible.

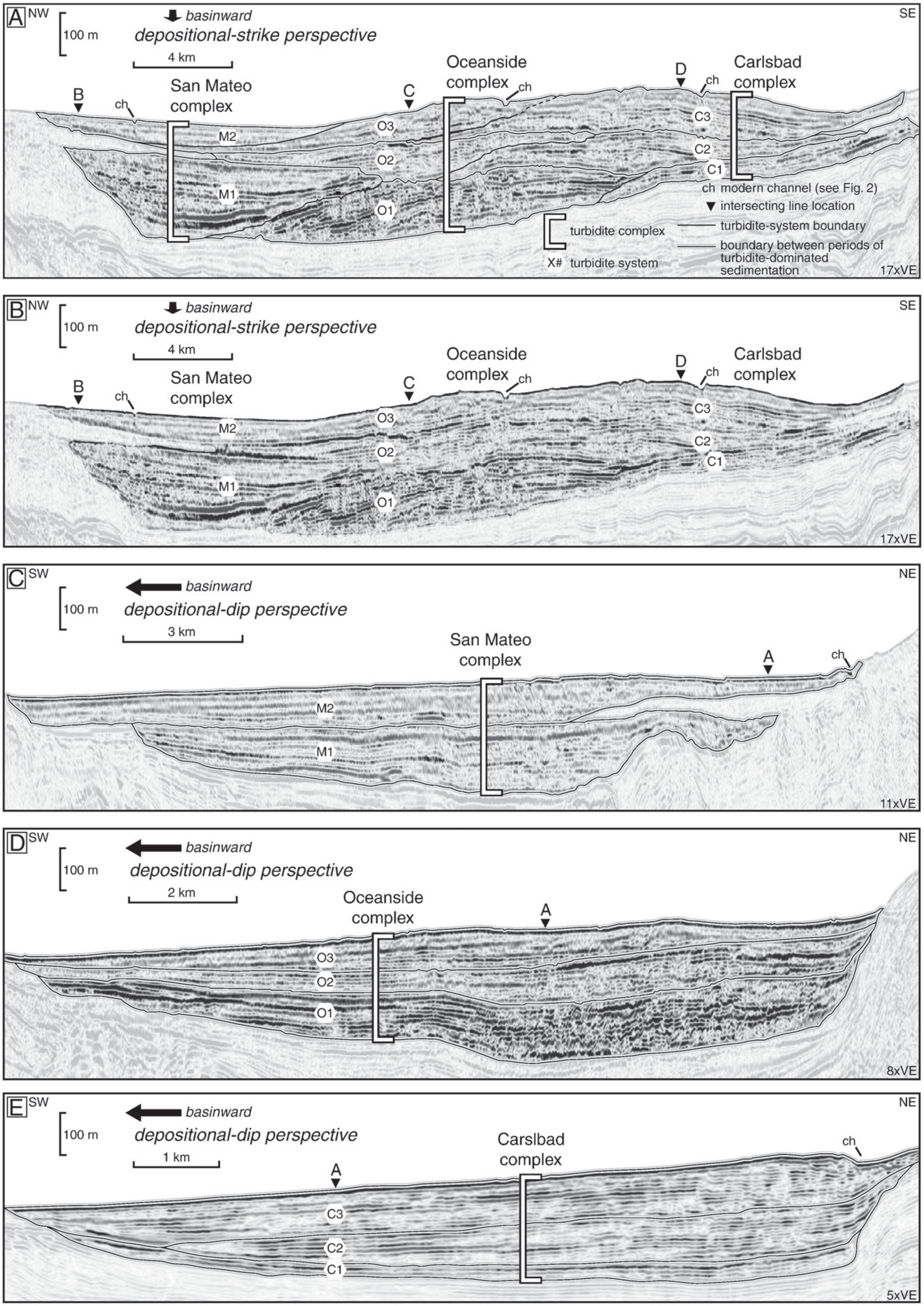
Ground truth of turbidite-system lithologies and ages since Oxygen Isotope Stage (OIS) 3 (45 ka) were determined from piston cores (3–5 m below seafloor, mbsf) collected during U.S. Geological Survey cruises O-2-99-SC and A-1-03-SC, and a deeper core (>70 mbsf) collected during experimental drilling into La Jolla Fan for Project Mohole (1958–1966; see Inman and Goldberg, 1963; and U.S. Geological Survey, 1999, 2003; for core locations; Covault et al., 2007). Records of box cores from the Scripps Institute of Oceanography Francis P. Shepard archives and published literature were also examined (Emery and Bray, 1962; Shepard and Einsele, 1962; Piper, 1970).

3.1. Turbidite-system recognition criteria and depositional-unit hierarchy

Studies of turbidite systems are based on different types of data, which provide different degrees of resolution and, therefore, exhibit different physical attributes of the deposits (Mutti and Normark, 1987). Feeley et al. (1985) used two-dimensional seismic-reflection data (including 12-fold multichannel and single-channel seismic-reflection data) in order to describe the major depositional units of the Mississippi Fan, which they called fan lobes, and to interpret the depositional processes of the fan lobes. Fan lobes are packages of turbidites that were deposited during discrete periods of canyon-and-channel activity, or growth phases, and are bounded by fine-grained strata that were deposited during intervening periods of deactivation (Feeley et al., 1985). Later, Weimer (1991) used higher-resolution two-dimensional seismic-reflection data (including 24- and 48-fold multichannel seismic-reflection data) and well data from the nine DSDP Leg 96 sites in order to study the Mississippi Fan. The dataset provided higher-resolution results than had been previously possible on the Mississippi Fan and focused on the characteristics and depositional processes of channel and overbank elements, which they called channel-levee systems. Channel-levee systems are turbidite depositional units that generally have the same hierarchical significance as the fan lobes of Feeley et al. (1985) (Weimer, 1991); however, the higher-resolution data used in the Weimer (1991) study allowed for more detailed analysis of channel-(levee)–overbank characteristics and processes.

In the context of this study, turbidite systems were recognized in seismic-reflection data following criteria of Mutti and Normark (1987, 1991), Posamentier and Erskine (1991), and Normark et al. (1993) (Figs. 3 and 4). Turbidite systems are commonly hundreds of meters thick, lenticular in cross section, and conform to receiving-basin

Fig. 4. Seismic-reflection profiles showing turbidite complexes and component systems in the southeastern Gulf of Santa Catalina. (A) Depositional-strike perspective of turbidite depositional units. Carlsbad system 1 (C1), Oceanside system 1 (O1), and San Mateo system 1 (M1) were deposited during the first period of turbidite-dominated sedimentation. Carlsbad system 2 (C2) and Oceanside system 2 (O2) were deposited during the second period of sedimentation. Carlsbad system 3 (C3), Oceanside system 3 (O3), and San Mateo system 2 (M2) were deposited during the third period of sedimentation. Dashed turbidite-system boundaries indicate likely interdigitation between C3 and O3. (B) Part A without interpretation for comparison. (C) Depositional-dip perspective of San Mateo complex and component systems. (D) Oceanside complex and component systems. (E) Carlsbad complex and component systems. See Fig. 2 for seismic-reflection profile locations. See Fig. 5 for approximate ages of first, second, and third periods of turbidite-dominated sedimentation.


A NW
SE
100 m
basinward
depositional-strike perspective
4 km
B
ch
San Mateo complex
M2
M1
C
O3
O2
O1
Oceanside complex
ch
D
ch
C3
C2
C1
Carlsbad complex
ch modern channel (see Fig. 2)
▼ intersecting line location
turbidite complex
turbidite-system boundary
boundary between periods of turbidite-dominated sedimentation
X# turbidite system
17xVE
B NW
SE
100 m
basinward
depositional-strike perspective
4 km
B
ch
San Mateo complex
M2
M1
C
O3
O2
O1
Oceanside complex
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C3
C2
C1
Carlsbad complex
17xVE
C SW
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depositional-dip perspective
3 km
San Mateo complex
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D SW
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100 m
basinward
depositional-dip perspective
2 km
Oceanside complex
A
O3
O2
O1
8xVE
E SW
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100 m
basinward
depositional-dip perspective
1 km
Carslbad complex
A
ch
C3
C2
C1
5xVE

Table 1
Turbidite-system morphologic characteristics.

Turbidite system	Volume (km^3)	Area (km^2)	Maximum thickness (m)	Length (km)	Width (km)
Confined California Borderland					
Carlsbad system 1 (C1)	3	93	106	13	10
Oceanside system 1 (O1)	28	286	245	23	19
San Mateo system 1 (M1)	35	364	279	28	20
Carlsbad system 2 (C2)	9	178	151	21	14
Oceanside system 2 (O2)	17	345	146	26	20
Carlsbad system 3 (C3)	19	287	180	23	20
Oceanside system 3 (O3)	31	693	160	57	24
San Mateo system 2 (M2)	20	381	133	27	23
Confined GOM slope basins					
Basin II lower sequence	–	48	70	10	8
Basin II middle sequence	–	66	70	11	8
Basin II upper sequence	–	134	80	15	12
Basin IV lower fan	–	43	100	10	6
Basin IV upper fan	–	112	96	16	9
Unconfined settings					
Youngest Mississippi fan lobe	–	104,748	400	602	264
Amazon Upper Levee Complex	–	45,647	500	411	128
Indus channel-levee complex VE 2	–	154,927	400	665	290
Bengal subfan D	–	732,380	400	1410	667

GOM slope Basin II sequences from Beaubouef and Friedmann (2000).
GOM slope Basin IV fans from Beaubouef et al. (2003).
Youngest Mississippi fan lobe from Bouma et al. (1985c).
Amazon Upper Levee Complex from Damuth et al. (1983, 1988).
Indus channel-levee complex VE 2 from Droz and Bellaiche (1991) and Kenyon et al. (1995).
Bengal subfan D from Curray et al. (2003).

geometry in plan view (Mutti and Normark, 1987, 1991; Posamentier and Erskine, 1991; Normark et al., 1993) (Table 1; Figs. 3 and 4). Systems represent erosion and deposition by sediment-gravity flows during periods of virtual stratigraphic continuity, commonly lasting several thousands to hundreds of thousands of years (and referred to as growth phases in this study; Mutti and Normark, 1987). The canyons and channels that fed sediment to turbidite systems are identifiable on the seafloor and in the relatively shallow subsurface (Figs. 3 and 4). Turbidite systems primarily occur as submarine fans (Weimer and Link, 1991), which have well-developed channel-(levee)–overbank elements (Nelson et al., 1978; Bouma et al., 1985a), and include relatively unconfined lobes (or splays) at the distal ends of channels and on the overbank region where channel levees are breached (Normark et al., 1993; Posamentier and Kolla, 2003). Component elements of turbidite systems are recognized in this study (especially in high-resolution seismic-reflection data; Mutti and Normark, 1987, 1991; Normark et al., 1993); however, detailed aspects of individual elements are difficult to resolve and are beyond the focus of this study. Mutti and Normark (1987) attributed the difficulty in recognition of component elements and their vertical organization on tectonically active continental margins and continental to transitional crust (e.g., in the California Borderland) to relatively short growth phases and high-frequency, and essentially similar, sediment-gravity flows. Ground truth of seismic reflections is provided from U.S. Geological Survey piston cores and the Mohole drill core (Inman and Goldberg, 1963; U.S. Geological Survey, 1999, 2003); however, it is difficult to comprehensively diagnose turbidite-system lithologies, especially at depth. Seismic reflections at the margins of turbidite systems commonly exhibit a high-amplitude character as a result of relatively large impedance contrast between the systems and their bounding surfaces. The large impedance contrast is likely a result of the interface between the relatively coarse-grained sediment composing turbidite systems and finer-grained, hemipelagic sediment composing bounding surfaces (Mutti and Normark, 1987).

California Borderland turbidite systems generally have the same hierarchical significance as the fan lobes or channel-levee systems composing the Mississippi Fan (cf., p. 255 of Feeley et al., 1985; and p. 29 of Mutti and Normark, 1987; who related individual fan lobes to separate fans, or turbidite systems, with distinct physiographic, morphologic, and depositional zones), levee complexes composing the Amazon Fan (Damuth et al., 1983, 1988; Damuth and Flood, 1985; Manley and Flood, 1988; Flood et al., 1991; Flood et al., 1997), channel-levee complexes composing the Indus Fan (Kolla and Coumes, 1987; Droz and Bellaiche, 1991; McHargue, 1991; Kenyon et al., 1995), and subfans composing the Bengal Fan (Curray et al., 2003) (Table 1). Stacks of turbidite systems that were fed sediment from canyons and channels during multiple growth phases form composite bodies, which are turbidite complexes (Mutti and Normark, 1987, 1991) (Table 2; Figs. 3 and 4). Relatively short-lived California Borderland turbidite complexes are hundreds of meters thick and formed on continental to transitional crust where continuing tectonic activity resulted in relatively rapid changes in basin morphology and in short-lived sediment sources (i.e., type D basins of Mutti and Normark, 1987) (Table 2; Figs. 3 and 4). Longer-lived turbidite complexes (e.g., the modern Mississippi, Amazon, Indus, and Bengal complexes) can be up to several kilometers thick and formed on oceanic crust with voluminous, longer-lived sediment sources and little or no tectonic activity (i.e., type A basins of Mutti and Normark, 1987) (Table 2). In both cases, turbidite complexes represent multiple turbidite-system growth phases. However, the longer-lived Mississippi, Amazon, Indus, and Bengal complexes were built as a result of many more growth phases and, as a result, are distinctly larger than Borderland complexes (Table 2; Figs. 3 and 4).

3.2. Timing of turbidite-system growth

Covault et al. (2007) constructed a chronostratigraphic framework of turbidite-system growth phases in the southeastern Gulf of Santa Catalina and San Diego Trough since OIS 3 (i.e., younger than 45 ka); however, the precise timing of growth phases before OIS 3 is unknown. When sea level lowered to the depth of canyon heads, and remained at that depth or lower for a prolonged period (several thousands to tens of thousands of years; cf., Mutti and Normark, 1987), canyon heads received sediment from littoral drift and terrestrial drainages and, as a result, canyons and channels supplied sediment to turbidite systems (see Fig. 3 of Covault et al., 2007; cf., sequence-stratigraphic models of turbidite-system growth, including Vail et al., 1977; Mitchum, 1985; Posamentier et al., 1988, 1991; and Posamentier and Vail, 1988). Therefore, before OIS 3, the depth of canyon heads at the shelf edge below present sea level is used in order to approximate the timing of

Table 2
Turbidite-complex morphologic characteristics.

Turbidite complex	Volume (km^3)	Area (km^2)	Maximum thickness (m)	Length (km)	Width (km)
Confined California Borderland					
Carlsbad complex	32	311	364	24	21
Oceanside complex	77	793	423	57	21
San Mateo complex	56	429	390	29	20
Confined GOM slope basins					
Basin II complex	–	134	150	15	12
Basin IV complex	–	112	200	16	9
Unconfined settings					
Mississippi complex	290,000	300,000	4000	700	564
Amazon complex	700,000	330,000	4200	860	592
Indus complex	1,000,000	1,100,000	3000	1500	960
Bengal complex	4,000,000	3,000,000	16500	2800	1100

GOM slope Basin II complex from Beaubouef and Friedmann (2000).
GOM slope Basin IV complex from Beaubouef et al. (2003).
Mississippi complex from Barnes and Normark (1985) and Bouma et al. (1985a,b).
Amazon complex from Barnes and Normark (1985) and Damuth et al. (1983, 1988).
Indus complex from Barnes and Normark (1985) and Droz and Bellaiche (1991).
Bengal complex from Barnes and Normark (1985) and Curray et al. (2003).

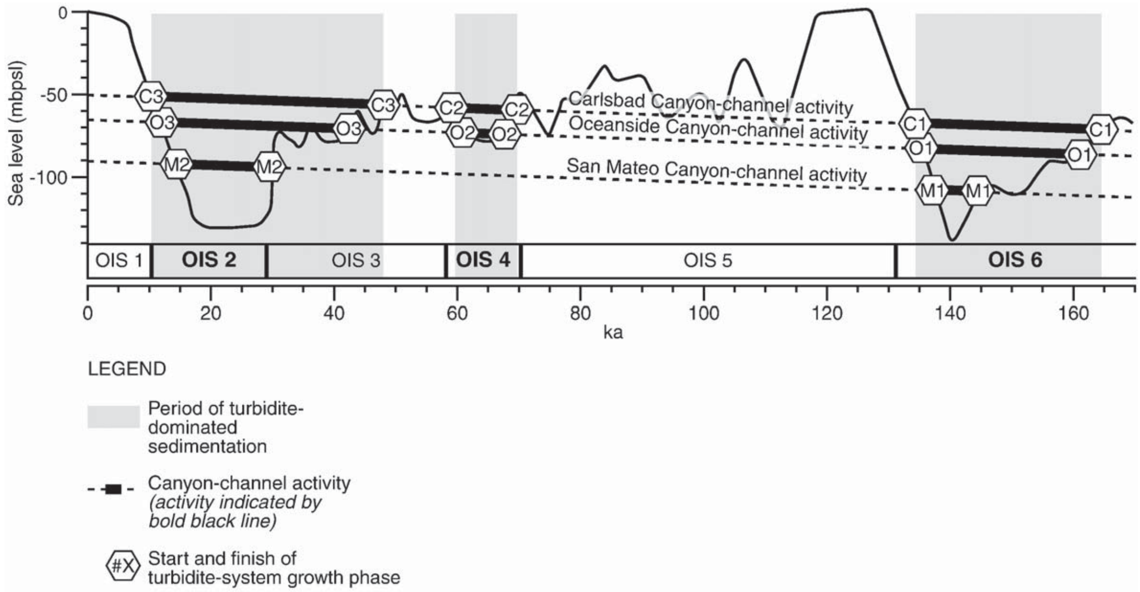


Fig. 5. Canyon-and-channel activity according to sea-level fluctuations since OIS 6. Sea-level curve from Lambeck and Chappell (2001) and Siddall et al. (2007). Dashed black lines indicate the approximate depth of canyon heads since OIS 6, and increase with age according to a regional uplift rate since ~1.5 Ma of 0.13 m/ky (Kern and Rockwell, 1992). When sea level is less than or equal to canyon-head depths, canyons and channels are interpreted to be active, and turbidite-system growth occurs (indicated by bold black lines bounded by hexagons). Three periods of turbidite-dominated sedimentation are shaded: OIS 6, OIS 4, and OIS 3–2. Relative timing of turbidite-system growth phases indicated by superposed turbidite systems in seismic-reflection data corresponds with timing predicted by depths below present sea level of shelf-edge canyon heads (cf., Fig. 4A).

turbidite-system growth (Fig. 5). In order to account for the influence of regional uplift of the shelf on canyon-head depth, we increased canyon-head depths according to a regional uplift rate since ~1.5 Ma of 0.13 m/ky (Kern and Rockwell, 1992) (Fig. 5). A potential source of uncertainty in determining past canyon-head locations is the assumption that canyon-head position remained constant through time. Precise timing is not necessary in this study in order to interpret the relative morphologic variability of turbidite systems and composite complexes; rather, *relative* timing of turbidite-system growth phases is of fundamental importance. Relative timing in the California Borderland was easily determined on the basis of stratigraphic stacking (Figs. 3 and 4A).

4. Results

4.1. Deep-water sedimentation since OIS 6

Eight turbidite systems were recognized in the southeastern Gulf of Santa Catalina and San Diego Trough: three each composing the Oceanside and Carlsbad turbidite complexes and two composing the San Mateo turbidite complex (Figs. 4, 6, and 7). Systems accumulated over periods as long as tens of thousands of years and approach a maximum thickness of 300 m (cf., Mutti and Normark, 1987) (Table 1; Figs. 4 and 6). The relative timing of turbidite-system growth phases indicated by superposed turbidite systems in seismic-reflection data corroborate the timing predicted by depths below present sea level of shelf-edge canyon heads (see also radiocarbon age-based findings of Covault et al., 2007) (Figs. 4A and 5). Systems can be differentiated in seismic-reflection data, even though they were synchronously growing during lower stands of sea level, because they did not synchronously initiate (Fig. 5). Another factor that contributed to differentiation of systems is that the majority of their growth likely occurred during marine regression, when submarine sediment instabilities were accentuated (Posamentier and Allen, 1999). The relatively coarse-grained turbidite systems were predominantly draped by transgressive and highstand hemipelagic mud between regressive growth phases (Posamentier and Allen, 1999). For example, Carlsbad system 2 initiated growth later during marine regression than Oceanside system 2 and, as a result, subsequent Oceanside system 2 strata lapped onto older Carlsbad system 2 strata (Fig. 4). It is likely that there is interdigitation of systems at scales finer than those resolved in the seismic-reflection data of this study.

There were three periods of turbidite-dominated sedimentation, during each of which the Carlsbad turbidite complex initiated turbidite-system growth first, followed by the Oceanside complex, and, if sea level lowered significantly, the San Mateo complex grew last (Figs. 4A and 5). The first and second periods occurred during the OIS 6 and 4 sea-level lowstands, respectively. The third period occurred during the OIS 3 marine regression and OIS 2 sea-level lowstand and early transgression (cf., Covault et al., 2007). During the third period, at 40 ka, Oceanside system 3 filled the southeastern Gulf of Santa Catalina to its spill point and, as a result, a connection to the San Diego Trough was established (Covault et al., 2007) (Fig. 7G).

4.2. Turbidite-system and -complex morphology

Turbidite-system volumes range from 3 to 35 km^3 (Table 1). The total volumes of sediment supplied to the Borderland basins were comparably large during OIS 6 and 3–2 (66 km^3 and 70 km^3, respectively), and small during OIS 4 (26 km^3) (Table 1). System areas range from 93 to 693 km^2; maximum thicknesses range from 106 to 279 m (Table 1; Figs. 6, 7, and 8A). System lengths and widths were measured along their long and intermediate axes, respectively. Long axes are commonly oriented approximately parallel to the shelf (Fig. 6C). Lengths range from 13 to 57 km; widths range from 10 to 24 km (Table 1; Figs. 6C and 8B).

Turbidite-complex volumes range from 32 to 77 km^3; areas range from 311 to 793 km^2; maximum thicknesses range from 364 to 423 m; lengths range from 24 to 57 km (Table 2; Fig. 6). All three complexes are ~20 km wide (Table 2; Fig. 6). Within each complex, ratios of component system thickness to area are progressively smaller (Fig. 9A). This is because system areas increased more than maximum thicknesses during successive growth phases (Table 1). The areas of the most recently deposited systems (i.e., Carlsbad system 3, Oceanside system 3, and San Mateo system 2, which grew during OIS 3–2) are >87% of the areas of their complexes (Fig. 9B).

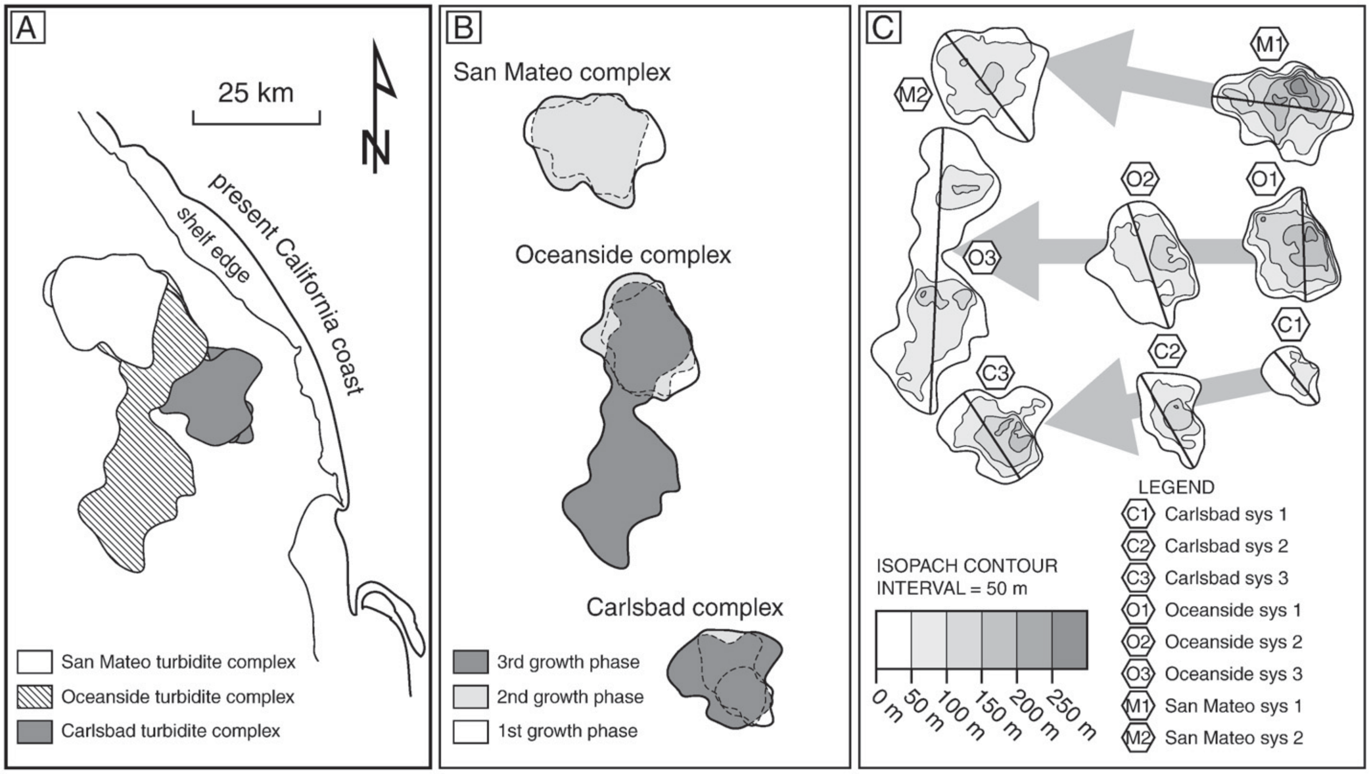


Fig. 6. Plan and three-dimensional representations of turbidite complexes and component systems. (A) Turbidite complexes relative to present southern California coast and shelf edge. (B) Turbidite complexes with areal extents and relative timing of component systems. (C) Isopach maps of turbidite systems. Systems are organized into rows according to complex. Arrows indicate sequence of system growth phases within a complex. Black lines are system long axes.

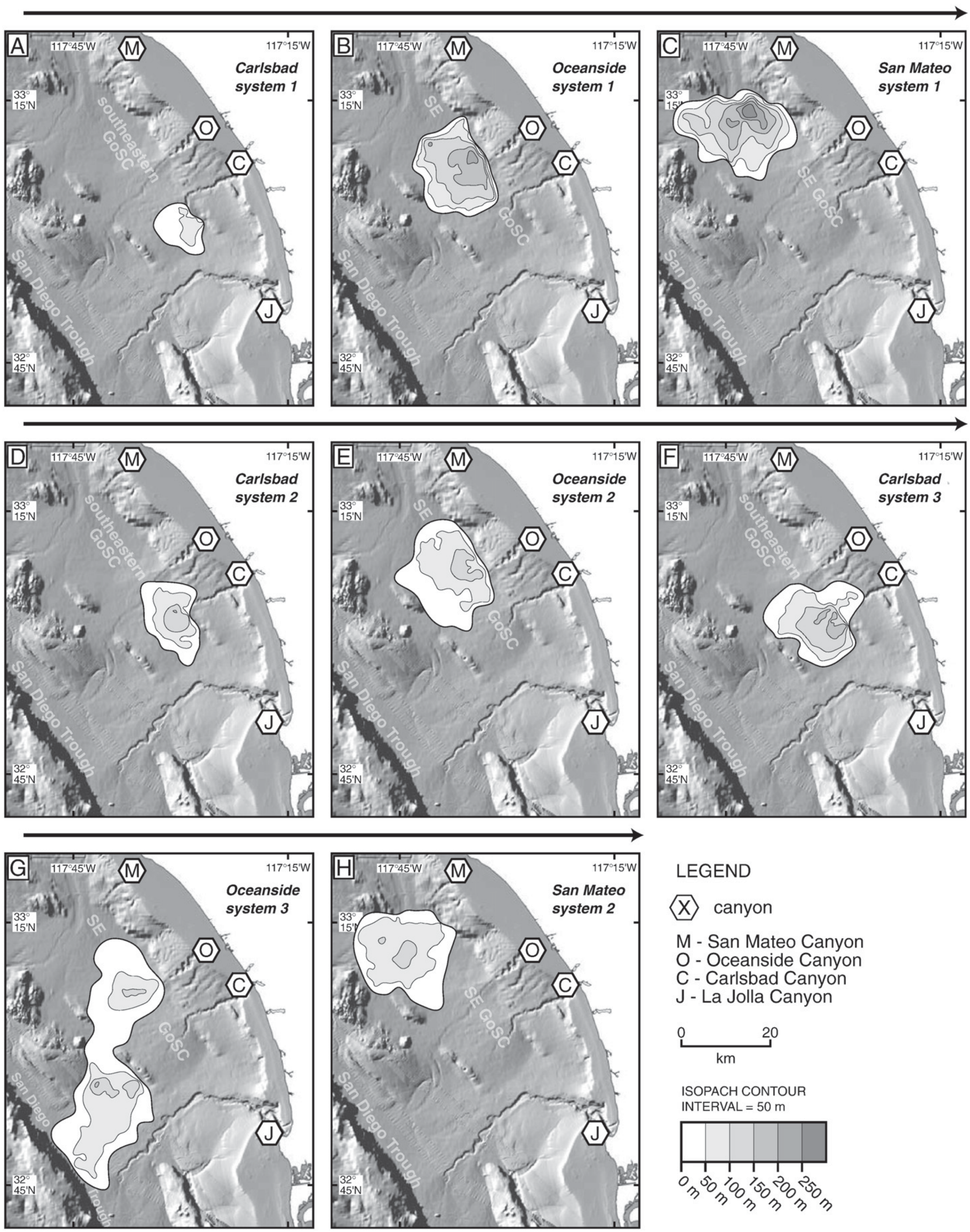
4.3. Interpretations of growth and morphology

California Borderland turbidite-system morphologic variability is related to the interplay between volume of sediment supplied and receiving-basin geometry. Both of these influencing factors vary between turbidite-system growth phases. The volumes of sediment supplied to turbidite systems vary related to external conditions, which include climate, terrestrial drainage-basin area, relief, and lithology (Milliman and Syvitski, 1992; Inman and Jenkins, 1999; Syvitski and Milliman, 2007; Allen, 2008). Receiving-basin geometry in the California Borderland evolves as a result of progressive turbidite deposition (Gorsline and Emery, 1959). Gorsline and Emery (1959) developed the first model of confined receiving-basin evolution in the Holocene Santa Monica and San Pedro basins of the northern California Borderland. They observed that basins located in the outer Borderland are underfilled, whereas inner basins are filled nearly to bounding bathymetric highs and are relatively broad and flat (Gorsline and Emery, 1959). Their model showed that large turbidite sedimentation rates in nearshore basins resulted in rapid filling and smoothing of relatively high-relief bathymetry, followed by spilling of sediment into progressively seaward basins (Gorsline and Emery, 1959). In this way, receiving basins can expand from a single nearshore basin to include a seaward basin as a result of sufficiently voluminous turbidite deposition. This growth pattern is also reflected in the Tertiary development of the Monterey Fan offshore central California (Fildani and Normark, 2004). Fildani and Normark (2004) showed that the Neogene Lower Monterey Turbidite System "healed" relatively high-relief bathymetric irregularities. The subsequent late Quaternary Upper Monterey Turbidite System was less confined and spread out across the relatively broad and flat seafloor (Fildani and Normark, 2004).

Fig. 7 shows that when turbidite systems are confined by their receiving-basin margins, and are relatively voluminous, they are relatively thick. This is likely because turbidite systems that were supplied a large enough volume of sediment to be confined by their basin margins were unable to areally expand and, as a result, subsequent turbidite deposition thickened the systems (e.g., Oceanside system 1 and San Mateo system 1). Conversely, insufficient volumes of sediment to extend systems to their receiving-basin margins resulted in thinner systems (e.g., Carlsbad systems 1 and 2). In this way, turbidite-system morphology is related to the interplay between volume of sediment supplied and receiving-basin geometry. This is best demonstrated by comparing Oceanside systems 1 and 3, which were supplied nearly equal volumes of sediment, but grew in different-sized receiving basins (Fig. 7B and G). Oceanside system 1 was supplied sufficient sediment to extend to the margins of the southeastern Gulf of Santa Catalina (Fig. 7B). Areal extension beyond the basin's margins was not possible and, as a result, subsequent turbidite deposition produced a thicker system (Fig. 7B). The younger Oceanside system 3 was supplied a similar volume of sediment (Table 1); however, its receiving-basin geometry was very different (Fig. 7G). The southeastern Gulf of Santa Catalina was filled to its bounding ridges during growth of Oceanside system 3. As a result, its receiving basin included not only the southeastern Gulf of Santa Catalina, but also the seaward San Diego Trough. Oceanside system 3 was less confined by the margins of the enlarged receiving basin and is thin and areally extensive relative to Oceanside system 1 (Fig. 7G).

Scatter plots of turbidite-system morphologies support our interpretation that morphologic variability is related to the interplay between

Fig. 7. Areal extents of Borderland turbidite systems relative to present bathymetry. (A) Carlsbad system 1. (B) Oceanside system 1. (C) San Mateo system 1. (D) Carlsbad system 2. (E) Oceanside system 2. (F) Carlsbad system 3. (G) Oceanside system 3. (H) San Mateo system 2. Oceanside system 1 and San Mateo system 1 were supplied large enough volumes of sediment to extend to their receiving-basin margins and thicken. Carlsbad systems 1 and 2 were not supplied sufficient volumes to extend to their basin margins and are thinner. Bathymetry courtesy of Peter Dartnell (Gardner and Dartnell, 2002; Dartnell et al., 2007).


A
117°45'W
117°15'W
33° 15'N
32° 45'N
M
O
C
J
Carlsbad system 1
southeastern GoSC
San Diego Trough
B
Oceanside system 1
SE GoSC
C
San Mateo system 1
D
Carlsbad system 2
E
Oceanside system 2
F
Carlsbad system 3
G
Oceanside system 3
H
San Mateo system 2
LEGEND
canyon
M - San Mateo Canyon
O - Oceanside Canyon
C - Carlsbad Canyon
J - La Jolla Canyon
0
20
km
ISOPACH CONTOUR INTERVAL = 50 m
0 m
50 m
100 m
150 m
200 m
250 m

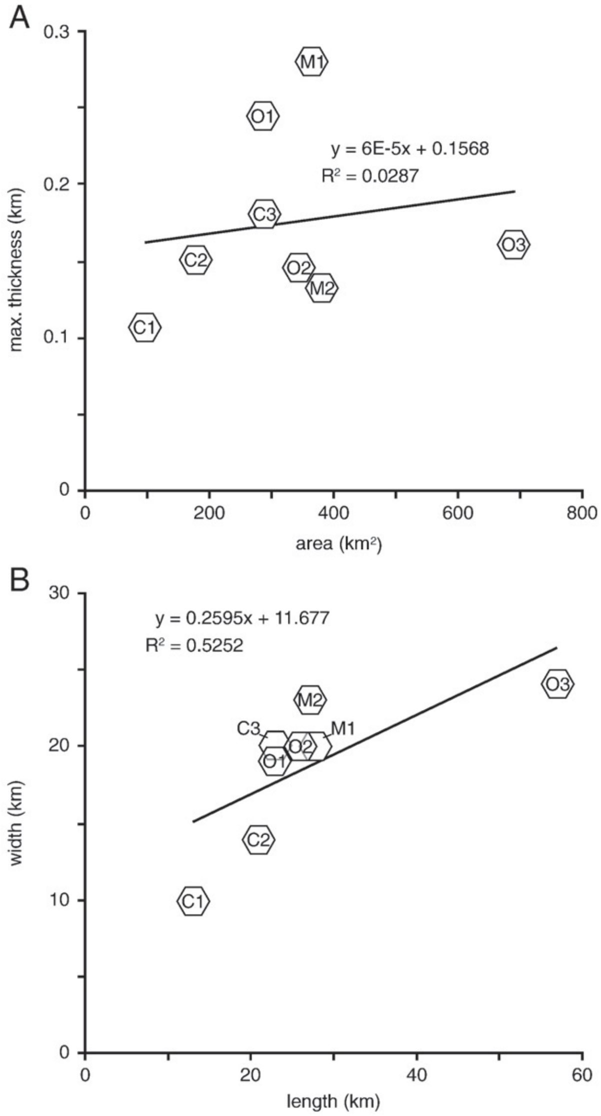


Fig. 8. Scatter plots of Borderland turbidite-system morphologic characteristics. (A) Areas versus maximum thicknesses. (B) Lengths versus widths. See Table 1 for area, thickness, length, and width values. See Fig. 6C for legend of turbidite-system abbreviations.

volume of sediment supplied and receiving-basin geometry (Fig. 10). Fig. 10A shows a plot of system volumes versus areas. Most turbidite systems, regardless of sediment volume, are less than 400 km^2 in area. This is likely because systems were unable to extend beyond the margins of the southeastern Gulf of Santa Catalina. Therefore, 400 km^2 is an upper limit for system areas in the southeastern Gulf of Santa Catalina. A single system, Oceanside system 3, which was discussed above, filled an enlarged receiving basin, and, as a result, it is relatively areally extensive (<700 km^2).

Fig. 10B shows a plot of turbidite-system volumes versus maximum thicknesses. The plot exhibits a weak positive relationship. This suggests, intuitively, that larger volumes of sediment correspond with thicker systems. Oceanside system 3, however, is an outlier. As discussed above, Oceanside system 3 received a relatively large volume of sediment, but it grew in an enlarged receiving basin and, as a result, it is thinner than systems of comparable volume.

Fig. 10C shows a plot of ratios of turbidite-system area to receiving-basin area versus system maximum thicknesses. Receiving-basin area was measured for the southeastern Gulf of Santa Catalina (~1300 km^2). The area of the San Diego Trough is from Emery (1960) (~1800 km^2). For simplicity, receiving-basin area was assumed to be the area of the southeastern Gulf of Santa Catalina during all turbidite-system growth phases except during Oceanside system 3 growth. The receiving-basin area during Oceanside system 3 growth was the combined areas of the southeastern Gulf of Santa Catalina and San Diego Trough (3100 km^2). The most areally extensive turbidite system only covers ~30% of its basin area; however, as shown in Fig. 7, turbidite systems can be relatively thick without covering their entire basin floor as long as they contact their opposing basin margins. The plot exhibits a weak positive relationship. This is because systems that cover a larger proportion of their receiving basins are more likely to significantly thicken if supplied a

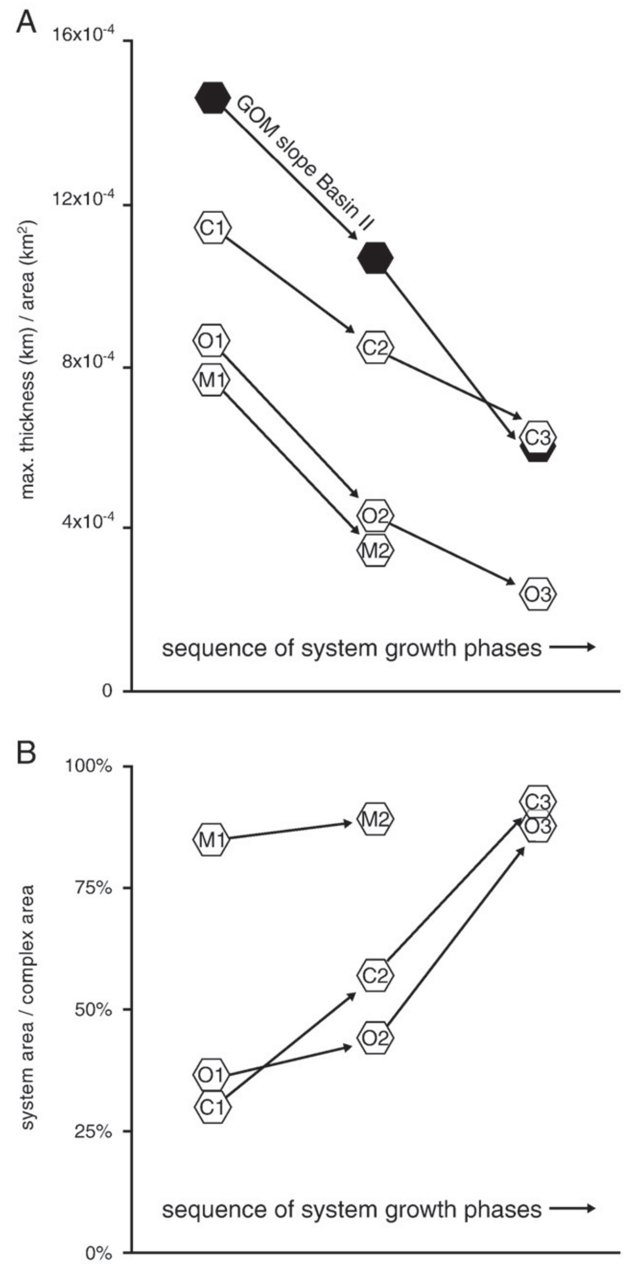


Fig. 9. Evolution of Borderland turbidite-system morphologies. (A) Evolution of maximum thickness-to-area ratios. Systems exhibit progressively smaller thickness-to-area ratios. Black hexagons represent progressively smaller thickness-to-area ratios of turbidite systems in the confined salt-withdrawal Basin II of the western Gulf of Mexico slope (Beaubouef and Friedmann, 2000). Gulf of Mexico slope turbidite systems are discussed in section '5. Discussion: Comparison to turbidite systems in confined and unconfined settings.' (B) Proportions of component systems to their composite complexes. Systems are progressively more similar in areal extent to their complexes. See Tables 1 and 2 for system and complex thickness and area values.

relatively large volume of sediment. Oceanside system 1, San Mateo system 1, Oceanside system 2, and San Mateo system 2 have similarly large ratios of turbidite-system area to receiving-basin area, but different thicknesses. As discussed above, different thicknesses are likely a result of differences between volume of sediment supplied and receiving-basin geometry. Oceanside system 1 and San Mateo system 1 were supplied sufficient sediment to extend to the margins of their receiving basins and subsequent turbidite deposition thickened the systems. Oceanside system 2 and San Mateo system 2 were not supplied a large enough volume of sediment to create thicker systems once they had grown to their receiving-basin margins.

Gorsline and Emery's (1959) early model of confined receiving-basin sedimentation is reflected in the evolution of turbidite systems in the southeastern Gulf of Santa Catalina and San Diego Trough. Component systems within each complex exhibit progressively smaller maximum thickness-to-area ratios, i.e., system areas increased more than maximum thicknesses during successive growth phases (Fig. 9A). The most recently deposited systems, which grew during OIS 3–2, are similar to the areas of their complexes (Fig. 9B). As advocated by Gorsline and Emery (1959), this is most likely a result of progressive turbidite deposition “healing” relatively high-relief bathymetry (i.e., smoothing local bathymetric “pot holes”) until the southeastern Gulf of Santa Catalina was filled to its bounding ridges and subsequent turbiditic sediment spilled into the seaward San Diego Trough at 40 ka (Fig. 11A).

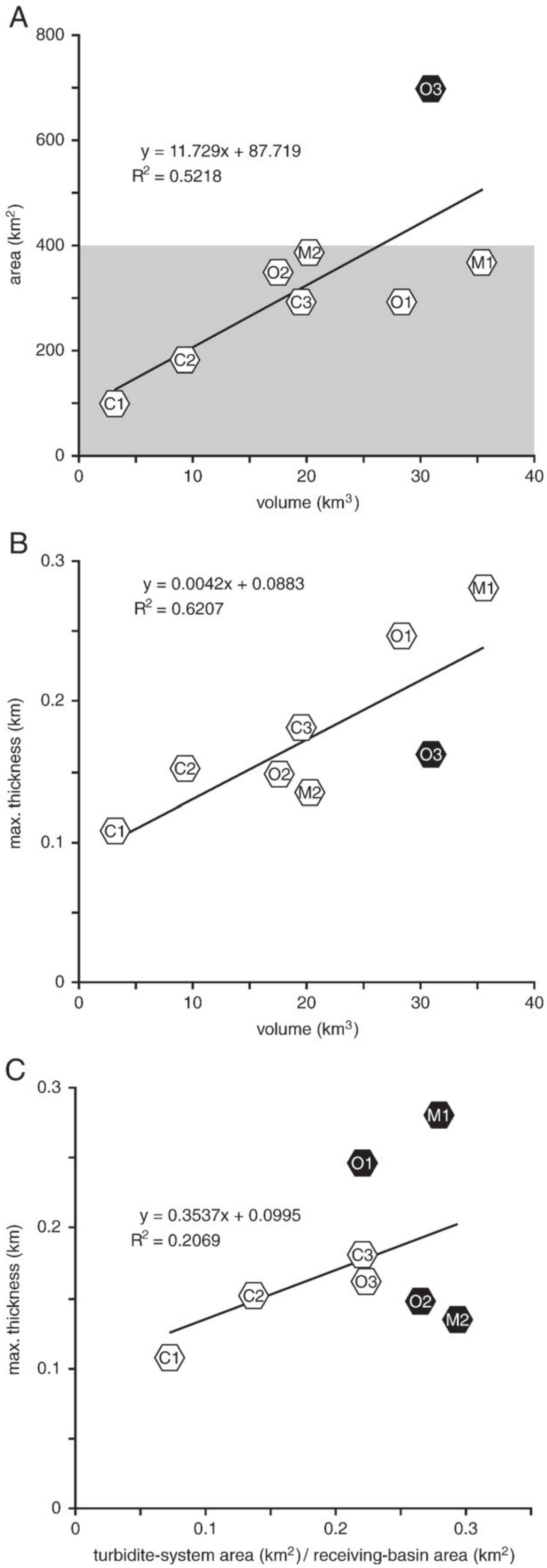


Fig. 10. Scatter plots of Borderland turbidite-system morphologic characteristics. (A) Volumes versus areas. Areas ≤ 400 km^2 are shaded gray. Oceanside system 3 (O3) is an outlier highlighted in black. (B) Volumes versus maximum thicknesses. Oceanside system 3 (O3) is an outlier highlighted in black. (C) Ratios of turbidite-system area to receiving-basin area versus system maximum thicknesses. Oceanside systems 1 and 2 and San Mateo systems 1 and 2 are highlighted in black.

5. Discussion: Comparison to turbidite systems in confined and unconfined settings

5.1. Small, confined turbidite systems

Modern Gulf of Mexico intraslope basins and their turbidite fills have recently received attention as a result of the increased economic importance of turbidite-reservoir exploration in analogous settings (including the Gulf of Mexico subsurface, and offshore west Africa and Brazil; Mutti et al., 2003). In the western Gulf of Mexico, the extensively studied Brazos–Trinity slope includes salt-withdrawal basins up to 16 km long and 10 km wide (basins II and IV are best documented and analyzed by, among others, Beaubouef and Friedmann, 2000; Beaubouef et al., 2003; and Mallarino et al., 2006). These basins were fed relatively fine-grained sediment from the small Brazos and Trinity rivers and associated deltas (the Brazos River drains an order of magnitude smaller area, and has two orders of magnitude smaller sediment load, than the Mississippi River; Milliman and Syvitski, 1992; Mulder and Syvitski, 1995). The entire sedimentary fill of a salt-withdrawal basin composes a turbidite complex, which includes distinctive sequences approximately equivalent to turbidite systems of this study (Beaubouef and Friedmann, 2000; sequences are referred to as fans by Beaubouef et al., 2003; or units by Mallarino et al., 2006). System, or sequence, areas range from 43 to 134 km^2; maximum thicknesses range from 70 to 100 m; lengths range from 10 to 16 km; widths range from 6 to 12 km (Table 1; Fig. 12). The complexes in basins II and IV are 134 and 112 km^2 in area, respectively; maximum thicknesses are 150 and 200 m; lengths are 15 and 16 km; widths are 12 and 9 km (Table 2). Component systems exhibit progressively smaller maximum thickness-to-area ratios (cf., Figs. 9A and 11A).

5.2. Large, unconfined turbidite systems

Early collaborative research efforts provided a wealth of information regarding turbidite systems and larger-scale complexes on oceanic crust with ample sediment supplied from extensive terrestrial drainages and little or no tectonic activity (e.g., the Mississippi, Amazon, Indus, and Bengal complexes and component systems; Bouma et al., 1985b; Mutti

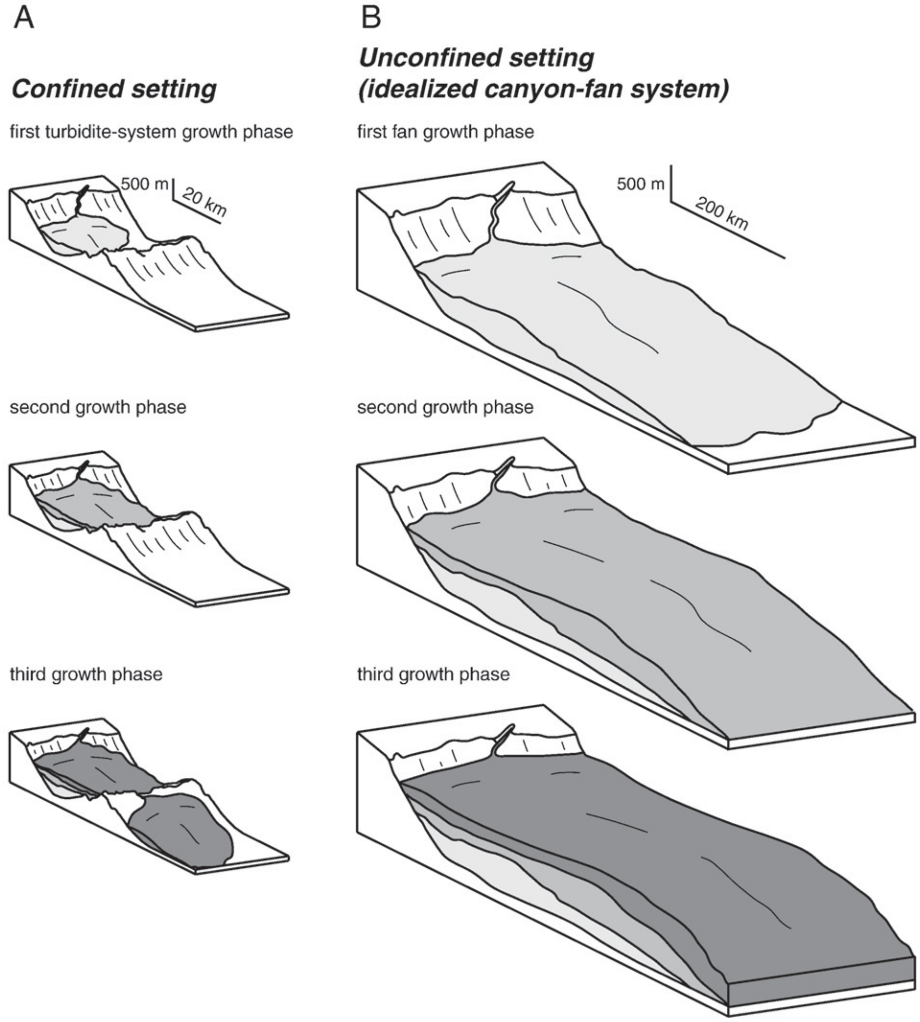


Fig. 11. Summary diagrams of turbidite depositional-unit growth in confined and unconfined settings. (A) Growth in the California Borderland and analogous settings with confined receiving basins. This diagram reflects growth of the Oceanside turbidite complex, which filled the southeastern Gulf of Santa Catalina and spilled into the seaward San Diego Trough (cf., Gorsline and Emery, 1959; Prather et al., 1998). Systems are progressively more areally extensive and thin as a result of turbidite deposition "healing" relatively high-relief bathymetry. (B) Growth in unconfined ocean basins with sediment supplied from extensive terrestrial drainages. This diagram reflects growth of the Indus turbidite complex (Kolla and Macurda, 1988). Voluminous, finer-grained unconfined systems were unrestricted by basin margins and grew to be distinctively areally extensive. Approximate scales for A and B are adjacent to the first growth phase diagrams.

and Normark, 1987; and Weimer and Link, 1991). These complexes received predominantly finer-grained sediment from some of the largest rivers in the world for millions of years (Kolla and Coumes, 1987; Mutti and Normark, 1987; Milliman and Syvitski, 1992; Wetzel, 1993), during which time they grew, unconfined by receiving-basin margins, across the floors of large ocean basins (i.e., type A basins of Mutti and Normark, 1987). The youngest component systems range in area from 45,600 to 732,400 km^2; maximum thicknesses range from 400 to 500 m; lengths range from 400 to 1500 km; widths range from 100 to 700 km (Table 1; Fig. 12). Complex areas range from 300,000 to 3,000,000 km^2; maximum thicknesses range from 3000 to 16,500 m; lengths range from 700 to 2900 km; widths range from 500 to 1200 km (Table 2). Unconfined systems are extremely voluminous (Table 1); however, their maximum thickness-to-area ratios are extremely small (Fig. 12).

5.3. Comparison

California Borderland and Gulf of Mexico intraslope turbidite systems have comparably large thickness-to-area ratios (Fig. 12); however, they have distinctively smaller areal characteristics (i.e., area, length, and width) relative to large, unconfined systems (Table 1). These morphologic relationships result from differences between the caliber and total volume of sediment supplied and receiving-basin geometry. Relatively meager volumes of sediment supplied to confined turbidite systems results in larger thickness-to-area ratios (Figs. 11A and 12). When the total volume of sediment supplied to these small, confined turbidite systems is sufficiently large, they grow to basin margins and thicken (Fig. 11A). Large, unconfined systems were supplied much larger volumes of sediment in unrestricted ocean basins and, as a result, grew to be distinctively areally extensive (this interpretation was highlighted in works by Nelson and Kulm, 1973; Pickering, 1982; Kolla and Coumes, 1987; Normark, 1985; Stow et al., 1985; Mutti and Normark, 1987; Kolla and Macurda, 1988; Shanmugam and Moiola, 1988; Wetzel, 1993; Apps et al., 1994; Reading and Richards, 1994; Prather et al., 1998; Booth et al., 2000; Piper and Normark, 2001; and Fildani and Normark, 2004; to name a few) (Tables 1 and 2; Fig. 11B). It is important to keep in mind that the durations of turbidite-system growth phases are comparable between settings discussed here (i.e., thousands of years; Mutti and Normark, 1987). Sediment caliber also contributes to turbidite-system growth and morphology (Nelson and Kulm, 1973; Stow et al., 1985; Mutti, 1992; Wetzel, 1993; Reading and Richards, 1994). The large, unconfined fans received predominantly finer-grained sediment, which facilitated sediment-gravity-flow run-out distance (i.e., efficient flows; Mutti, 1992) and the development of extensive leveed channel systems

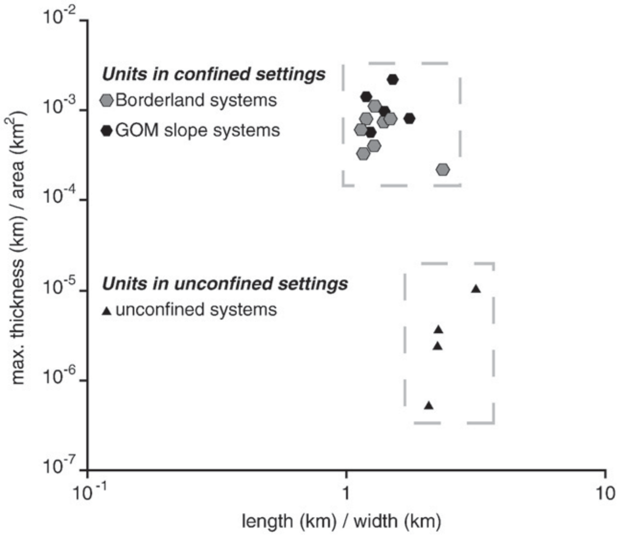


Fig. 12. Scatter plot of modern turbidite-system morphologic characteristics in confined and unconfined settings. Length-to-width ratios versus maximum thickness-to-area ratios. Confined and unconfined depositional units plot in distinct clusters (identified by dashed gray boxes). Thickness-to-area ratios of confined systems are at least one order of magnitude larger than ratios of unconfined units. Symbol key is to the left. See Tables 1 and 2 for area, maximum thickness, length, and width values.

across low-gradient, areally extensive fans (Nelson and Kulm, 1973; Stow et al., 1985; Mutti, 1992; Wetzel, 1993; Reading and Richards, 1994).

In both confined settings of the California Borderland and western Gulf of Mexico slope, component systems within each complex exhibit progressively smaller maximum thickness-to-area ratios (Fig. 9A). This is a result of comparable processes of progressive turbiditic basin filling (Gorsline and Emery, 1959; Prather et al., 1998; Fig. 11A). Prather et al. (1998) described ponded and bypass acoustic facies of Gulf of Mexico intraslope basin fill from seismic-reflection data, and attributed the facies to varying sediment supply and accommodation geometry (i.e., salt-withdrawal receiving-basin geometry; see also Apps et al., 1994; Beaubouef and Friedmann, 2000; Booth et al., 2000; and Beaubouef et al., 2003). Prather et al. (1998) noted that the transition from ponded to bypass facies reflects the transition from rugose, relatively high-relief basin-floor bathymetry to a smoother and more graded bathymetric profile as a result of progressive turbidite deposition (cf., Gorsline and Emery, 1959; Fig. 11A). This is similar to basin filling in the California Borderland, where progressively smaller thickness-to-area ratios are a result of turbidite deposition smoothing relatively high-relief bathymetry, followed by spilling of sediment into progressively seaward basins (Gorsline and Emery, 1959).

Accommodation renewal in Gulf of Mexico intraslope basins occurs as a result of subsidence related to sediment loading and salt withdrawal (Pratson and Ryan, 1994; Booth et al., 2000; Twichell et al., 2000). 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). During periods of reduced sediment supply, the rate of basin subsidence (which is 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; see Fig. 10 of Twichell et al., 2000). This process of accommodation renewal is distinctively different from deformation-induced subsidence in the California Borderland. Borderland basins deform primarily as a result of lithospheric plate movements and are more resistant to slight, short-term sediment loading (i.e., turbidite-system growth) relative to gravity-driven passive-margin settings (Rowan et al., 2004).

Although the dominant grain sizes of Borderland and western Gulf of Mexico slope turbidites are different (i.e., Borderland turbidites are relatively coarse grained), and Gulf of Mexico intraslope basins subside as a result of sediment loading and salt withdrawal (Pratson and Ryan, 1994), the comparably small volumes of sediment supplied to systems (which represent tens to hundreds of thousands of years of sedimentation in both settings; Beaubouef and Friedmann, 2000) and confined receiving-basin geometries produced similar morphologies (Fig. 12). However, the larger proportion of relatively coarse-sized grains supplied to California Borderland basins likely inhibited areal expansion of turbidite systems by reducing flow efficiency (Mutti, 1992), whereas accommodation renewal of Gulf of Mexico intraslope basins likely enhanced turbidite-system thicknesses. Similar thickness-to-area ratios, therefore, are likely a result of other influences in addition to meager volumes of sediment supplied and receiving-basin confinement.

5.4. Areal characteristics of turbidite systems

Length-to-width and length-to-area ratios are within the same order of magnitude for all turbidite systems regardless of setting (Figs. 12 and 13). Van Wagoner et al. (2003) suggested that similar length-to-area ratios of depositional bodies are a result of the inherent dissipative behavior of the fundamental flows that create bodies. During the development of a depositional body, component elements are progressively organized toward the periphery of the body as channelized flows respond to gradient and deposit their sediment load in local accommodation in transit to or at the periphery of the body. Diminished confinement and gradient at the periphery of the body result in rapid deceleration, depletion, and consequent deposition of the flow (Lowe, 1982; Kneller, 1995; McCaffrey and Kneller, 2004). These processes produce the familiar radial, tree-like morphology inherent to many depositional bodies (e.g., deltas and turbidite systems), and inhibit the development of extremely long bodies (e.g., length-to-width ratios of turbidite systems are typically not larger than 10:1).

Sediment-gravity-flow processes and larger-scale autogenic behavior (e.g., channel avulsion, lobe switching, etc.) certainly are important in influencing turbidite-system morphology, particularly areal characteristics (Fig. 13); however, receiving-basin geometry can be important in tectonically complex, relatively confined settings (Pickering, 1982). In particular, receiving-basin geometry can significantly thicken (Fig. 12) and elongate turbidite systems. The Eocene Broto turbidite system developed in an elongated (>100 km long, tens of kilometers wide) wedge-top basin of the south-central Pyrenees, Spain (Mutti, 1992; Remacha and Fernandez, 2003). Ricci Lucchi (1986) characterized elongated Tertiary turbidite complexes in foredeep basins (hundreds of kilometers long; tens of kilometers wide) of the Apenninic fold-thrust belt, Italy. Fildani and Normark (2004) showed relatively elongated sediment pathways of the Neogene Lower Monterey Turbidite System. Reid and Normark (2003) characterized the elongated modern Tufts Fan offshore the Pacific northwest of the United States, whose areal morphology is a result of linear ridge-and-valley bathymetry of the western flank of the high-relief Gorda Ridge oceanic spreading center.

Although length-to-width ratios are comparably similar between turbidite systems, the absolute values of length and width vary over three orders of magnitude (Fig. 13). The largest lengths and widths correspond with the Mississippi, Amazon, Indus, and Bengal turbidite systems (Fig. 13). These systems grew during periods comparably similar to Borderland and western Gulf of Mexico systems (i.e., several thousands to tens of thousands of years; Mutti and Normark, 1987); however, the distinctively larger volumes of finer-grained sediment supplied and unconfined receiving basins facilitated several orders of magnitude more areally extensive, longer, and wider systems (Fig. 13).

6. Conclusions

This study departs from recent analyses of the relatively fine-scale geomorphology and internal architecture of turbidite systems and

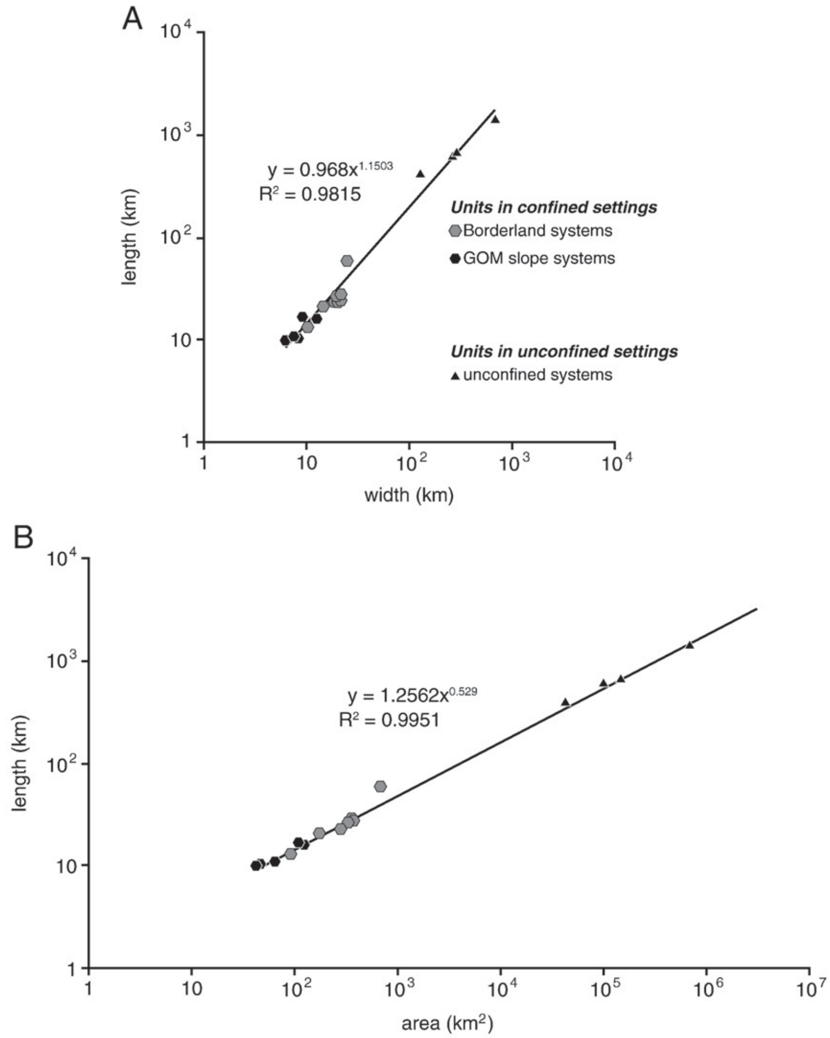


Fig. 13. Scatter plots of modern turbidite-system areal characteristics in confined and unconfined settings. (A) Widths versus lengths. (B) Areas versus lengths. Areal characteristics of depositional units are positively related. Symbol key is to the right in A. See Tables 1 and 2 for area, length, and width values.

characterizes growth and gross morphologies of systems and larger-scale complexes in confined basins of the California Borderland. Turbidite-system morphologies were quantified according to volume, area, maximum thickness, length, and width using an extensive grid of seismic-reflection data. Turbidite systems that were supplied a large enough volume of sediment to be confined by their basin margins were unable to areally expand and, as a result, subsequent turbidite deposition thickened the systems. Conversely, insufficient volumes of sediment to extend systems to their receiving-basin margins resulted in thinner systems. Within each turbidite complex, component system areas increased more than maximum thicknesses during successive growth phases. This is most likely a result of progressive turbidite deposition “healing” relatively high-relief bathymetry until a nearshore basin was filled to its bounding ridges and subsequent turbidity currents spilled into a seaward basin. The growth and morphologies of turbidite systems in the relatively confined basins of the California Borderland are similar to systems in the western Gulf of Mexico as a result of similarities between the volumes of sediment supplied and receiving-basin geometries. Voluminous, finer-grained, unconfined systems were unrestricted by basin margins and, as a result, grew to be distinctively areally extensive in large ocean basins. Fine-scale analyses of turbidite architecture allow for assessment of sediment-gravity-flow mechanics and larger-scale autogenic behavior of elements within systems, and facilitate development of turbidite hydrocarbon-reservoir models. However, fine-scale turbidite architecture alone represents only a small part of the turbidite depositional record, and this study shows that the larger-scale nature of the entire turbidite systems is influenced by external controls, including caliber and volume of sediment supplied and receiving-basin geometry. Insights into the growth of the entire turbidite systems in confined basins can be integrated with finer-scale observations and interpretations from analogous settings in order to develop more comprehensive turbidite-system models.

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