Submarine Lobe Deposits of the Point Loma Formation, California: Quantifying Event-Bed Architecture and Lateral Heterogeneity

Rosemarie C. Fryer\textsuperscript{1,*}, Zane R. Jobe\textsuperscript{1,**}, Fabien Laugier\textsuperscript{2}, Luke A. Pettinga\textsuperscript{1}, J. Clark Gilbert\textsuperscript{1}, Lauren E. Shumaker\textsuperscript{1}, James E. Smith IV\textsuperscript{1,***}, and Morgan Sullivan\textsuperscript{2}

1. Department of Geology and Geological Engineering, Colorado School of Mines, Golden Colorado 80401
2. Chevron Energy Technology Company, Houston Texas 77002
* Now at Hilcorp Energy Company, Houston Texas 77002
** corresponding author zanejobe@gmail.com
*** Now at USDA Agricultural Research Service, Oxford Mississippi

Abstract

Over the last several years, numerous outcrop localities have been revisited to add quantitative detail to submarine lobe facies models that previously focussed on facies relationships in a qualitative sense. This study utilises well-exposed submarine lobe deposits of the Point Loma Formation in Cabrillo National Monument (San Diego, CA) to provide quantitative and statistical insights into the lateral
variability of event-bed (i.e., turbidite) architecture within and between lobe elements. Within a lobe element (defined as a surface-bounded, genetically related package), event beds compensationally stack, thinning over subtle sea floor topography created by the previous event bed. Between lobe elements, larger-scale compensation is observed, with clearly defined stratal surfaces and facies architecture distinguishing the four lobe elements. A lateral facies transition is observed for one lobe element, where sandstone beds pinch out and the element thickness halves over a distance of 100 m.

However, architectural parameters of event beds (e.g., bed thickness, thinning rate, fining rate) are not appreciably different between these elements, suggesting that the observed stratal architecture does not readily translate into vertical bed thickness (i.e., stacking) patterns that could be easily recognised in common subsurface data types like borehole-derived core. While the data derived from this outcrop study is valuable for improving the construction of realistic geologic and reservoir models, caution is necessary when interpreting lobe element boundaries from borehole data.

The lobe deposits measured in this study have event-bed thicknesses and thinning rates most similar to semi-confined proximal lobes, suggesting a more proximal position and more confined than previously interpreted. Based on relationships between sandstone and mudstone thicknesses and thinning rates, bed and lobe-element compensation, and minimal evidence of erosion, the Point Loma Formation at Cabrillo National Monument is reinterpreted as a medial lobe environment with some degree of lateral and/or frontal confinement.

Keywords: submarine fan, pinch out, thinning rate, turbidite, hybrid event bed

Introduction

Submarine lobe environments are the terminal portions of deep-marine depositional systems and are classified as broad, unconfined locales where high aspect-ratio, sand-rich, sediment gravity flow
deposits emanate from submarine channels (Normark, 1970; Piper and Normark, 2001; Morris et al., 2014; Picot et al., 2016; Pettinga et al., 2018). Submarine lobe deposits are important archives of palaeoenvironmental change (Hessler and Fildani, 2019), but have been studied most rigorously to determine the distribution of sandy reservoirs for hydrocarbon accumulation (Bouma et al., 1985; Hofstra et al., 2017). Conceptual models of submarine lobe deposit architecture typically exhibit a decrease in bed thickness, grain size, sand content, and amalgamation in proximal-to-distal and axis-to-fringe transects (Normark, 1978; Sullivan et al., 2000; Deptuck et al., 2008; Prélat et al., 2009). The details of downstream and lateral facies changes are often overlooked or grossly simplified, even though many early studies recognised complexity in distal lobe environments (Nelson et al., 1992; Twichell et al., 1992; Schwab et al., 1996). Recent interest in these environments for petroleum exploration and carbon storage has resulted in new studies that indicate complex sea floor topography and facies architecture that challenge these simplistic, conceptual models; both recent sea floor/shallow subsurface (Talling et al., 2010; Carvajal et al., 2017; Dennielou et al., 2017; Jobe et al., 2017; Fildani et al., 2018) and outcrop (Spychala et al., 2017; Kane et al., 2017; Bell et al., 2018) examples show vastly more complexity than originally envisioned.

Because event-beds (i.e., turbidite deposits) are the building blocks of submarine fans (Jobe et al., 2018), quantitative evaluation of event-bed statistics (e.g., bed thickness, thinning rate) enables an improved understanding of the linkages between geomorphology and stratigraphy and how turbidity currents respond to a sea floor surface that is continually modified by previous flows and deposits (Prélat et al., 2009; Jegou et al., 2008; Romans et al., 2009; Jobe et al., 2017). This fine-scale heterogeneity is particularly important for building more realistic reservoir models for conventional and unconventional hydrocarbon developments hosted in submarine lobe deposits (Kerans et al., 1994; Haughton et al., 2009; Kane and Ponten, 2012; Hofstra et al., 2017). Yet, very few studies have
performed correlations at the event-bed scale (Chapin and Tiller, 2007; Marini et al., 2015; Fonnesu et al., 2015; 2018), and even fewer studies have compiled quantitative statistics on lateral thickness variability of individual turbidite deposits in submarine-lobe settings (Clark, 1998; Tőkés and Patacci, 2018; Fryer and Jobe, 2019).

Through a quantitative bed scale study of submarine lobe deposits of the Point Loma Formation exposed in San Diego, California, this study provides statistical insights into the lateral variability of event-bed architecture within and between lobe elements. These data were used to investigate the hierarchical nature of compensation in lobe deposits, and how well vertical event-bed stacking patterns represent 3D submarine lobe architecture. This rich dataset also provides insights for improving geologic and reservoir models for submarine lobe deposits, particularly in data-sparse subsurface settings where lateral facies variability at the bed scale is not observable.

**Geologic Background**

During the Late Cretaceous, the Rosario Group (Figure 1A) was deposited within a forearc basin caused by subduction of the Farallon Plate beneath the North American Plate (Atwater, 1970). The subsequent transition from convergent to transform continental margin tectonics around southern California resulted in extensive Cenozoic strike-slip deformation (Ingersoll, 2008) (Figure 1B). The Rosario Group is intermittently exposed as coastal outcrops along southern California and northern Mexico (Popenoe, 1973; Morris et al., 1989; Morris and Busby-Spera, 1990; Kane et al., 2007; 2009a; Kennedy et al., 2008; Hansen et al., 2017). At the base of the Rosario Group is the nonmarine, conglomeratic Lusardi Formation (Figure 1A), which is exposed north of San Diego and onlaps the pre-Turonian Santiago Peak Formation (Nordstrom, 1970; Peterson, 1970; Nilsen and Abbott, 1981). The Point Loma Formation, which unconformablyoverlies the Lusardi Formation, is interpreted as submarine slope to basin-floor mudstones and sandy lobe deposits (Figure 1) (Nilsen and Abbott, 1981).
Overlying the Point Loma Formation, sandstones and conglomerates of the Cabrillo Formation have been interpreted as coarse-grained inner to middle submarine fan deposits (Nilsen and Abbott, 1981), but are most likely conglomeratic submarine channel deposits (cf. Jobe et al., 2010). Eocene sandstones and conglomerates above the Cabrillo Formation are marked by a basal erosional unconformity and grade from shallow-marine deposits into a submarine-canyon complex (Figure 1) (Kennedy, 1975; May et al., 1991, May and Warme, 1991). In contrast to the Point Loma Formation, the Eocene deep-marine Scripps and Ardath formations exposed north of the La Jolla peninsula (Figure 1) have been extensively studied (Peterson, 1970; Kennedy and Moore, 1971; Kennedy, 1975; May et al., 1991; May and Warme, 1991; 2007; Stright et al., 2014; Ono and Plink-Bjorklund, 2017).

During the Campanian-Maastrichtian periods (84-66 Ma), the Point Loma Formation was deposited in a deep-marine forearc basin, likely one with relatively steep slope gradients (Nilsen and Abbott, 1981). The Point Loma was sourced from the Peninsular Ranges from the east; palaeoflow measurements indicate a west-northwest transport direction (Girty, 1987; Nilsen and Abbott, 1981; Fleming 2010). Post-depositional strike-slip motion related to plate boundary reorganisation resulted in ca 550 km of right-lateral translation and ca 40 degrees of rotation of the Point Loma Formation and its source, the Cretaceous Peninsular Ranges batholith (Marshall and McNaboe, 1984).

The Point Loma Formation is divided into three units: Unit 1 is a shallow marine sandstone, Unit 2 is dominated by slope mudstones and thin-bedded submarine fan deposits, and Unit 3 is dominantly thick-bedded submarine fan and channel deposits (Figure 1A) (Sliter, 1979; Nilsen and Abbott, 1981; Yeo, 1982). Using foraminiferal faunal assemblages, Units 2 and 3 are interpreted to have palaeobathymetric water depths of 850-1,000 m and 600-700 m, respectively (Figure 1; Sliter, 1979; 1984; Nilsen and Abbott, 1981). Within Units 2 and 3, Fleming (2010) documented four submarine lobe complexes that compensationally stack and display a systematic proximal-to-distal decrease in thickness.
in vertically amalgamated sandstone ratio, net sandstone to gross sediment thickness (‘net-to-gross’, also
known as net sandstone proportion), and erosion. Stammer (2014) studied an axis-to-fringe transect of a
lobe element that lies within Lobe Complex 2 of Fleming (2010). In this detailed transect, Stammer
(2014) documented an increase in mud content, mud clasts and organic matter, along with increases in
K-feldspar, plagioclase and biotite towards the fringe. McGlown (2015) documented axis-to-fringe
trends in grain size and bed thickness for both turbidites and hybrid event- beds in the Point Loma
Formation.

The deposits of the Point Loma Formation in the Cabrillo National Monument (Figure 1B) are the
focus of this study and are contained within Unit 2 of Nilsen and Abbott (1981) and Lobe Complex 3 of
Fleming (2010). Sea cliff exposures contain 1-50 cm sandstones interbedded with 1-10 cm mudstones
with a modal palaeocurrent direction of 294° (n = 167) (Figure 1B; Sliter, 1979; Nilsen and Abbott,
1981; Fleming, 2010; this study). The Cabrillo National Monument area is interpreted by Fleming
(2010) to represent four lobe elements within the distal part of Complex 3. However, rapid lateral
thickness changes occur at the bed scale, which is not typical of distal lobe facies models (Walker and
Mutti, 1973; Ricci-Lucchi, 1975; Lien et al., 2003) but has been documented in other recent outcrop
studies (Groenenberg et al., 2010; Etienne et al., 2012; Spychala et al., 2015; 2017; Fonnesu et al.,
2016; 2018) and modern sea floor studies (Dennielou et al., 2017) of lobe deposits.

Methodology

Field Data Collection

This study characterises Point Loma Formation deposits using centimetre-scale graphic logs, bed
and bedset correlations, palaeocurrent analysis, and measurements derived from a photogrammetry-
based 3D outcrop model. Because every event bed was measured and correlated, traditional lithofacies
sensu Hubbard et al. (2008) were not defined. Approximately 40 sandstone-mudstone couplets (event-beds) were correlated between 13 graphic logs (S1-S13) that capture the entire stratigraphic interval and 6 logs (MS1-MS6) focused on a ca 5 m thick interval (Figure 1C). The typical lithologies and features of event-beds are summarised in Figure 2. Generally, event beds consist of sandstone-mudstone couplets with Bouma-type sedimentary structures (Bouma, 1962) that are interpreted as turbidites (Figure 2).

Care was taken to identify and separate individual event beds, the deposit from one turbidity current (Bouma, 1962; Lowe, 1982). Some event beds are amalgamated into one sandstone bed-set; these bed sets show flame structures and grain-size changes at event bed boundaries (Figure 2). Only one event bed (Bed “L”) is interpreted as a hybrid-event bed (sensu Haughton et al., 2009) due to lateral facies transitions between sandstone and mudstone, variable mud clast frequency, and swirly, deformed textures (similar to those found by Fonnesu et al., 2015; 2018). No mass transport deposits or debris-flow deposits were encountered at this locality, although they are present elsewhere in the Point Loma Formation (Fleming, 2010; McGlown, 2015). Rare inoceramid shells and a high diversity of bioturbation features are also present (Figure 2; see Kern and Warme, 1974 for an in-depth faunal study). Palaeocurrent indicators include parting lineations (n = 60), ripples (n= 8), flame top directions (n = 2) and megaflutes (n = 2; sensu Elliott, 2000), with a mean palaeoflow direction of 304°, corroborating measurements collected by Fleming (2010) further north along the peninsula (mean of 294°, Figure 1B).

The coastal exposure is divided into two areas, Area 1 to the north and Area 2 to the south (Figure 1C); limited outcrop exposure in the cove between the two areas prevent exact correlation of the lower interval between Areas 1 and 2. The trend of the outcrop is ca 010°, which is oblique to palaeoflow (304°), but closer to a strike-section than a dip-section. Due to lack of outcrop exposures along the true
strike and dip orientations, thinning rates were only measured along the outcrop extent; these rates
cannot be corrected for palaeoflow direction without imposing arbitrary thinning rates (see Figure 3).

Statistical Analysis

For statistical comparison, bed thickness and lateral distance are the two most important types of
data collected in this study. In the Point Loma Formation, bed thicknesses were collected from graphic
logs and lateral distance was collected from map measurements and GPS locations. The methods of
Fryer and Jobe (2019) were used to compute the rate of change of bed thickness as well as grain size.
Equation 1 was used to compute the thinning rate, a dimensionless number that enables comparison of
bed thickness changes over a lateral distance (Fryer and Jobe, 2019). Also computed was the ‘fining
rate’ (Equation 2), the rate of lateral change of grain size (using psi (ψ), defined as the log₂ value of the
grain size in millimetres, Parker and Andrews, 1985) within a bed between two graphic logs; the fining
rates were calculated using a mean and maximum grain size identified by hand lens and grain size card.
Thinning and fining rates were acquired in pairwise fashion (sensu Fryer and Jobe, 2019) for both sand
and mud lithologies to provide a spatial distribution of thinning rates and to decrease the sampling bias
created from variable spacing between log locations. A 2D kernel density estimation (KDE) was used to
calculate percent-volume contours of two cross-plotted variables, providing polygons that encompass a
percentage of the data (Fryer and Jobe, 2019); for example, 90% of the cross-plotted data falls within a
90% volume contour map. Net-to-gross ratios were calculated at graphic log locations by dividing the
total sandstone thickness by the total stratigraphic thickness.

Equation 1 (after Fryer and Jobe, 2019):

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Thinning rate = \( \frac{\Delta \text{ Thickness} (m)}{\Delta \text{ Distance} (m)} \)

Equation 2:

Fining rate = \( \frac{\Delta \text{ Grain Size} (\psi)}{\Delta \text{ Distance} (m)} \)

RESULTS

Point Loma Submarine Lobe Architecture

This study follows the submarine lobe hierarchy proposed by Deptuck et al., (2008), where four levels may exist: ‘beds’ deposited by an individual event/turbidity current; ‘lobe elements’ composed of stacked beds/bed sets associated with changes in channel-mouth position or small-scale avulsions; ‘composite lobes’ formed by one or more stacked lobe elements fed by a single channel; and ‘lobe complexes’ that develop when avulsions or significant channel migrations result in development of multiple lobe elements and/or composite lobes. In any given system, all four levels may not be recognisable or present (Deptuck et al., 2008). While modern sea floor studies allow direct mapping/coring of submarine lobe deposits (Picot et al., 2016; Jobe et al., 2017; Pettinga et al., 2018), outcrop studies must rely on criteria to define hierarchical levels, generally vertical stacking patterns and facies architecture (Prelat et al., 2009; Prelat and Hodgson, 2013). This study utilises the following qualitative criteria to identify four units interpreted as Lobe Elements One, Two, Three and Four (Figures 4 through 8): (1) visually distinctive packages of event beds with similar event-bed thicknesses, facies and architecture (e.g., lateral pinch-and-swell event-beds in Element One), (2) the presence of thick (> 10 cm) mud-prone packages with no thick sand beds (e.g., interval between Elements Three and Four).
Four), (3) the presence of event beds that rapidly change facies or thickness, and (4) the presence of laterally persistent deposits of consistent thickness that have a ‘draping’ geometry and form a correlation datum (pink interval in Figures 5 through 7). Four lobe elements were recognised based on these criteria, but there is not enough lateral exposure to constrain whether these lobe elements form one or more composite lobes or if they form a single lobe complex.

**Overview of lobe element architecture**

Element One is only partially exposed, event-beds display a pinch-and-swell architecture (Figure 7), but no spatial trends are apparent. Element Two shows a prominent southward thinning trend onto Element One (Figure 9), where basal Element Two beds pinch out against Element One, while upper Element Two beds thin or remain quasi-constant thickness over the top of Element One (Figure 7). The interval between Element Two and Three is used as a datum for correlations (pink unit in Figures 4 and 7) because it is laterally continuous and easily identified by abundant coarse-grained biotite and diagenetic calcite veins (Figures 2 and 8). Element Three thins towards the south and the sandstone beds display pinch-and-swell morphology (Figures 6 and 7). The base of Element Four is marked by a change in architectural style with a hybrid event bed deposit (Bed L in Figure 10). Element Four contains rhythmic sandstone-mudstone couplets of very similar thickness (ca 10 cm) that change minimally across the outcrop (Figures 5 and 7).

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Intra-Lobe Element Bed Architecture:

Results

Element One displays a complex pattern of event-bed thickening and thinning, with a pinch-and-swell pattern. In Area 1, poor exposure prevents correlation of every event bed, but where visible, sand beds thin to the north (Figures 5 and 7). In Area 2, Element One is well exposed, and numerous event-beds thin and thicken in an inconsistent pattern (Figures 6 and 7). In numerous locations, multiple sand beds thin and merge/amalgamate into one thick sand bed, and then split back into separate beds (Figure 7).

Event beds within Element Two (yellow in Figure 9) show two thinning trends: (1) a large-scale southward thinning and onlap/pinch-out onto Element One (Figure 6), and (2) a bed scale compensation trend (Figure 9). The sand beds thicker than 10 cm in Element Two are most affected by this compensation; sand beds thinner than 10 cm do not seem to have a consistent, recognisable compensational trend. For example, Bed A rapidly thins southward, with thinning rates greater than 0.5 cm/m, and the thickest portion of Bed B (50 cm) lies directly above the rapidly thinning portion of Bed A (Figure 9). The next two sand beds are very thin (ca 3 cm) and display negligible variation in thickness. However, the next thick sand bed, Bed C, shows compensation with Bed B: as B thickens into S8, the overlying Bed C thins (Figure 9). Then, as B thins southward from S8, C thickens to its highest recorded value (39 cm; Figure 9). The thin bed above C displays very minor thickness changes and the next bed (just below Bed D) displays a thickness trend similar to C (Figure 9). Beds D and E both thicken directly above where Bed C rapidly thins. This trend continues to step south, where Bed F is thickest directly above where Beds D and E thin (Figure 9). Finally, Bed G seems to step back northward, thinning onto the thick part of Bed F (Figure 9).
Within Element Three (green in Figure 10) in Area 1, bed-by-bed compensation is also documented over a 25 m lateral distance, but the compensation is more subtle and complex than in Element Two. The basal bed of Element Three (Bed J) consistently thins southward towards MS5 with a thinning rate of approximately 0.4 cm/m, then slightly thickens south of MS5 (Figure 10). The overlying bed (J2) thickens where J starts thinning (between MS1 and MS2; Figure 10), and Bed J3 shows more complex lateral thickness variability. The next thick bed, Bed K, shows a similar initial thinning trend as basal Bed J but thickens directly above J’s most rapid thinning, and Bed K2 thickens above where Beds J and K thin (Figure 10). Bed K also seems to show minor thickness variability in a pattern opposite that of the underlying J3 bed (Figure 10). Bed L is the only identified hybrid event bed (sensu Haughton et al., 2009) in the study area, and Bed L shows rapid thickness changes over short distances, with thinning rates ranging between -0.4 to 0.55 cm/m (Figure 10B). This rapid bed thinning and thickening is concurrent with a change from a sandstone-dominated to a mud-dominated lithology (Figure 10A). Bed L2 slightly thickens at MS5 above where L thins but displays minimal thickness variation across the 25 m interval in Figure 10B, with thinning rates nearing 0 cm/m (Figure 10). Lastly, Bed M shows similar thickness trends as Bed L, but the degree of thinning is significantly lower (Figure 10).

**Analysis**

Event-bed compensation internal to a lobe element occurs as consistent off-stacking of event beds in Element Two (Figure 9) and Element Three (Figure 10), demonstrating that a depositing turbidity current reacts to the subtle sea floor topography created by the previous event bed. Similar event-bed compensation has been seen in modern submarine lobe settings (Jobe et al., 2017). However, event beds
less than 10 cm thick rarely display bed compensation, which could suggest the size of the depositing flow has control on the extent of the bed scale compensation (Figures 9 and 10). This could also be
influenced by flow stratification where flows with concentrated near bed layers are steered by bed topography more than dilute flow where the deposits form from suspension. Flow rheology may also play a role, as the hybrid event bed (Bed L) is thicker than 10 cm but displays no compensation to the bed below while adjacent turbidite beds of similar thickness (Bed J and K) do show compensation (Figure 10). Compensational stacking is the tendency to for a deposit to preferentially fill topographic lows, with the magnitude of compensation typically decreasing from proximal to distal locations (Mutti and Sonnino, 1981; Sullivan et al., 2000; Cantelli et al., 2011; Fernandez et al., 2014). There have been two proposed methods for compensational stacking (fractal and hierarchical), which depend on either scale-invariant compensation (fractal) or variable compensation at different hierarchical scales, respectively (Mutti and Sonnino, 1981; Mutti and Normark, 1987; Deptuck et al., 2008; Prélat et al., 2009; Straub and Pyles, 2012). The increase in the degree of compensation from beds to elements indicates a hierarchical rather than fractal stacking method in these submarine lobe deposits (Straub and Pyles, 2012; Figure 9). For example, event beds B and C within Element Two (yellow) infill the topography created by lobe Element One (purple) (Figure 9). Once Element Two has minimised the relief created by Element One (purple), flows are able to redistribute the bed thickness more evenly across the depositional surface to create more tabular beds with low thinning rates (e.g., bed E, Figure 9).
Inter-Lobe Element Architecture

Results

Lateral sandstone net-to-gross ratios remain fairly consistent in Element One, although the base is not exposed (Figure 7B). Element Two shows a southward increase in net-to-gross from S1 to S8 (0.5 to 0.75) where bed scale compensation is occurring, then a decrease from S8 to S13 (0.75 to 0.45) where event beds thin and onlap onto Element One. Element Three shows two separate patterns of north to south decrease in net-to-gross between S1 to S4 and S6 to S10 (Figure 7B). Net-to-gross remains laterally consistent in Element Four (Figure 7A). While thinning rates are quite similar for all four Elements, there is a difference in sandstone bed thickness above and below the datum horizon - Elements One and Two have slightly thicker-bedded sandstones than Elements Three and Four (Figure 11B).

The vertical stacking pattern of sandstone bed thickness is commonly used to infer lobe element boundaries (Walker and Mutti, 1973; Prélat and Hodgson, 2013), but the four lobe elements display a wide variety of stacking patterns (Figure 7). In particular, a plot of sandstone bed thickness (Figure 8) shows that there is no easily discernible stacking pattern that separates each element. In other words, it would be difficult to correctly choose the element boundaries given only the 1D graphic log in Figure 8. A more quantitative comparison is needed, and Figure 11 compares the distributions of sand-bed and mud-interval thinning rates and thicknesses between the four elements. Generally, the four elements have strongly overlapping distributions (Figure 11). In particular, sand bed thinning rates and thicknesses are very similar for Elements One, Three and Four (Figure 11), but Element Two exhibits thicker sand beds that thin more dramatically. Mud-interval thinning rates are also very similar when comparing elements (Figure 11), but Element Four has somewhat thicker mud intervals than the other elements.
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Element Two displays statistically different bed thicknesses compared to Elements One and Three (Figure 11), which could indicate a shift in architectural position or sediment supply. While not statistically robust, the stratal architecture patterns above and below the datum interval (pink interval in Figure 7) are striking in that Elements One and Two have laterally variable architecture with thicker-bedded sands (suggestive of an off-axis environment) whereas Elements Three and Four have affinities to fringe environments, with more laterally persistent and thinner-bedded sands (Figure 11). These differences across the datum interval, in addition to its lateral continuity, suggest that the datum may form a lobe complex boundary where significant avulsion of the feeder channel has taken place (Deptuck et al., 2008). However, not enough lateral exposure exists to confidently interpret the hierarchical significance of this interval.

Spatial patterns of net-to-gross are commonly used to infer lobe architecture (Prélat et al., 2009), and indeed the facies change and bed compensation of Element Two is also observed as a lateral decrease in net-to-gross (Figure 7B). Element Three also shows a general southward decrease in net-to-gross (Figure 7B), but the outcrop is likely too small compared to the lobe element width/length to ascertain if this trend is localised or part of a larger thinning trend to the south. One potential downfall of the analysis in this study is that each lobe element contains thin beds (< 10 cm) regardless of the overall thickness patterns, and thus comparing net-to-gross values and event-bed parameters between lobe elements may be somewhat skewed. For example, as each event bed in a ‘thick-bedded’ element (e.g., Element Two) is traced laterally toward its pinch-out, it approaches similar thicknesses as event-beds in other, dominantly ‘thin-bedded’ elements (e.g., Element One), thus creating overlap in distributions of event-bed thinning rate and thickness (Figure 11). To test this concept, the thin sand beds were filtered out from the analysis; however, no statistical difference between elements was found using various bed-thickness filters. However, the study area is small (width of ca 600 m x thickness of ca 10 m) compared...
to the dimensions of modern lobe elements (Pettinga et al., 2018) and at best, the outcrops at Cabrillo National Monument probably only sample one half of the lateral extent of a single lobe element; thus, the distribution of event-bed thickness and thinning rate (Figure 11) may under-represent deposits not locally exposed.

Discussion

Comparison to Other Submarine Lobe Deposits

Using the database developed by Fryer and Jobe (2019), it was possible to compare event-bed parameters from the Point Loma Formation to other lobe deposits as well as other submarine depositional environments (Figure 12). The Point Loma Formation displays thicknesses and thinning rates (sand and mud combined) most closely aligned to other lobe deposits (Figure 12A). Typical bed thickness in the Point Loma is slightly thinner than most lobe deposits measured by Fryer and Jobe (2019) (Figure 12), a finding attributed to the detailed nature of this study. While most studies do not measure and correlate beds < 10 cm thick, any sand bed > 1 cm was measured, and any bed > 2 cm was correlated; thus, the 90% volume contour polygon and centroid for the Point Loma Formation is slightly thinner bedded than most other lobe deposits (Figure 12A). When sand-bed and mud-interval data are plotted separately (Figure 12C), the Point Loma and other lobe deposits have very similar sand-bed and mud-interval thicknesses and thinning rates, while other environments have significantly different distributions. Thus, the Point Loma Formation at Cabrillo National Monument can be confidently interpreted as submarine lobe deposits.
To further refine the depositional environment of the Point Loma Formation, the degree of confinement from other lobate outcrops interpreted by Fryer and Jobe (2019) was used to assess the similarities and differences in bed-scale parameters (Figure 12B,D). The Point Loma Formation is most comparable in thickness and thinning rate (sand and mud combined) to semi-confined lobe deposits (Figure 12B). When split by lithology, the intermediate and approximately equal values of sand-bed and mud-interval thickness, lack of amalgamation, and larger thinning rates in sand beds compared to mudstone intervals (Figure 12D) also suggests that the Point Loma is semi-confined rather than unconfined (cf. Fleming, 2010). The abrupt thinning of Element Two in the study area (Figure 6) may also be evidence of a semi-confined setting, where lobe elements thin rapidly onto intra-basinal topography (Tőkés and Patacci, 2018), which is common in forearc basin environments (McAdoo et al., 2000) like that of the Point Loma Formation.

Lobe Sub-Environments of the Point Loma Formation

The stratal architecture (e.g., Figure 6) and quantitative event-bed data (e.g., Figure 11) help to inform the overall position of the four lobe elements of the Point Loma Formation. For example, Fleming (2010) interpreted the Cabrillo area as distal lobe deposits but did not perform detailed bed scale correlations. The results of this investigation shows that Element Two abruptly (over 50 m) and compensationally thins against Element One (Figure 9), architecture not common in distal lobe environments. Furthermore, the lack of observed erosion/amalgamation but common presence of mud clasts and large sand calibre (grain size up to 0.5 mm; Figure 7) also supports a lobe position which is relatively energetic and not near a distal fringe. Instead, the study area is interpreted to occupy a medial or off-axis position, perhaps with complex sea floor topography caused by autogenic submarine-lobe depositional processes (Dennielou et al., 2017) and/or active-margin tectonism (Bersezio et al., 2009;
A hydrocarbon reservoir in this medial position would have low vertical connectivity compared to the lateral connectivity (Kv/Kh; Hofstra et al., 2017).

It is important to distinguish (1) the overall position of the study area on the depositional profile defined by the generalised facies architecture with (2) the interpreted position for each lobe element within an idealised lobe element (Spychala et al., 2017). The study area is interpreted to occupy an overall medial position, but there are facies, thickness and thinning rate differences between elements that are suggestive of inter-element compensation. While these interpretations are speculative because elements cannot be traced to their terminus, there are quantitative data (Figures 11 and 12), and qualitative observations (Figure 7) to support them. The presence of a distinctive datum horizon (Figure 2) separating lobe elements with different facies architecture (Figure 7) suggests that this boundary may represent a lobe complex boundary, with Elements One and Two occupying an off-axis environment and Elements Three and Four occupying a fringe environment. The megaflutes occur near (but not at) the datum, perhaps suggestive of this subtle change in lobe element stacking, as is interpreted in other lobe systems (Elliott, 2000); however, an autogenic mechanism for megaflute formation cannot be ruled out (Kane et al., 2009b).

Elements Three and Four do not show large-magnitude thickness changes and/or compensation, suggesting they may occupy lateral-fringe rather than distal-fringe positions (Figure 7; Spychala et al., 2017); these elements also cannot be differentiated on the basis of event-bed thinning rates or thicknesses (Figure 11), perhaps indicating a subtle lateral switching of lobe elements rather than larger-scale compensational or progradational/retrogradational patterns. In other words, during lobe-element compensation, there was probably not a large change in either lobe dimension or position in the study area for Elements Three and Four (assuming there were no large changes in lobe-element dimensions). However, the common sandstone bed pinchouts in Element One and the rapid thinning of Element Two...
suggests a transitional zone from off-axis to a lateral fringe position, perhaps aided by local sea floor

topography. This transitional zone is quasi-strike-oriented (see palaeocurrent data in Figure 7), further

supporting a lateral facies change rather than a downslope (i.e., proximal-to-distal) facies change.

For medial and distal submarine lobe deposits, classical facies models indicate that sandstone bed

thickness changes minimally over hundreds of metres (Walker and Mutti, 1973; Ricci-Lucchi, 1975).

However, distal lobe deposits can also show abrupt thickness variations along strike, indicating a finger-

like “dendritic” pattern (Twichell et al., 1992; Prélat et al., 2009; Talling et al., 2010) rather than the

simple radial sheet geometry commonly found in schematic models (Mutti and Normark, 1987). The

'pinch and swell’ event-bed geometry found in Element One (Figure 7) and Elements Three and Four

(Figure 10) could be evidence of a dendritic lobe planform pattern, but no 3D exposure is available to

assess or refute this interpretation; also, the Point Loma bed pinch-and-swell is more subtle than that

documented in modern systems (Talling et al., 2010). Alternatively, the pinch-and-swell patterns may be

related to recently documented complexity in medial and distal lobe positions, including bedform

development (Baker and Baas, 2020), complex sea floor topography (Dennielou et al., 2017), and

downstream bed-thickness changes (Kane et al., 2017; Spychala et al., 2017).

Interpreting Lobe Element Boundaries in Subsurface Data

Even though there are well-defined stratal architectures that separate the lobe elements (Figures

5 through 7), the event-bed parameters (e.g., thinning rates, thicknesses) are very similar, with statistical

tests unable to differentiate Elements One, Three and Four (Figure 11). This similarity in event-bed

parameters suggests that using such data to differentiate lobe elements in 1D subsurface data (e.g., core,

well-log) should be performed with great caution. At any particular 1D location in the study area, the
stacking pattern rarely shows notable stacking pattern changes indicative of an element boundary (e.g., Figure 8); Prélal and Hodgson (2013) also found significant variability in vertical event-bed stacking patterns within and between lobe elements. In the study area, the locations where lobe element boundaries may be interpreted (e.g., based on thickness changes, Figure 8) do not always translate into a lateral heterogeneity that is apparent or important (in a connectivity sense) in the second dimension (e.g., lateral bed pinchouts documented in Figure 7).

This is critical when considering reservoir modelling decisions based on limited well penetrations. For example, reservoir model inputs are commonly determined from a single well or several wells that are ca 1 km apart (Jackett et al., 2014), and those wells may severely under-represent the vertical and spatial heterogeneity present, thereby having impacts on connectivity predictions. Rather than 1D stacking patterns, large lateral exposures are often needed to be able to identify stratal boundaries and associated connectivity between elements (Prélal et al., 2009). When comparing larger hierarchical levels (e.g., lobe complexes), vertical trends in event-bed parameters may be more apparent and thus easier to identify in borehole data, but thick, laterally continuous exposures of such deposits (including the Point Loma Formation) are uncommon due to the large scale of lobe complexes.

Conclusions

Using exceptional exposures of submarine lobe deposits of the Point Loma Formation in San Diego, California, this study provides quantitative and statistical insights into the lateral variability of event-bed architecture within and between lobe elements. Within an element, event-beds are compensatory in nature, thinning over subtle sea floor topography created by the previous event bed. However, beds thinner than 10 cm rarely display bed compensation, suggesting that only larger flows react to this topography. Larger-scale compensation is also observed between lobe elements, indicating a
hierarchical rather than fractal stacking method in these submarine-lobe deposits. Although clearly defined stratal surfaces separate four lobe elements, architectural parameters of event beds (e.g., bed thickness, thinning rate, fining rate) are not appreciably different between these elements. Only the sand-bed thickness from one element that abruptly onlaps another is distinguishable from other elements using a K-S test.

Event beds of the Point Loma Formation exposed at Cabrillo National Monument have been previously interpreted as distal lobe deposits, but the thinning rates and lateral bed variability recorded by this study are more complex than predicted by classic models of distal submarine lobe deposition. The event beds measured in this study have thicknesses and thinning rates most similar to semi-confined proximal lobes, suggesting a more proximal position and more confinement than previously interpreted. Based on relationships between event-bed thicknesses and thinning rates, bed and lobe-element compensation, and minimal evidence of erosion, this outcrop is reinterpreted as a medial lobe environment with some degree of lateral and/or frontal confinement, with at least one lateral fringe transition of a lobe element exposed.

The rich dataset produce in this study provides insights for analysing lateral heterogeneity in submarine lobe deposits, especially in data-limited settings where lateral facies variability at the bed-scale is not observable. This study shows that the observed stratal architecture caused by event-bed to event-bed interaction and compensation does not readily translate into vertical event-bed stacking patterns that could be recognised in common subsurface 1D data types (e.g., well-log, core). While the data derived from this outcrop study are valuable for improving the construction and parameterisation of realistic geologic and reservoir models, caution should be used when attempting to determine lobe element boundaries in 1D subsurface data.
The data that support the findings of this study are available on request from the corresponding author.

The data are not publicly available due to privacy or ethical restrictions.

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Supplemental Data

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FIGURES

Figure 1. Point Loma Formation, San Diego, CA. (A) Stratigraphic column modified from Nilsen and Abbott, 1981. (B) Map of study area on the Point Loma Peninsula in San Diego, California (modified from Fleming, 2010). (C) Satellite image of Cabrillo National Monument (location shown as black box in part B), which is subdivided into Area 1 and Area 2. Black dots are graphic log locations, shown in Figures 4 and 6.

Figure 2. Event beds of the Point Loma Formation. Parts A-E describe the lithologies present, and part (F) describes other pertinent features present at Cabrillo National Monument.

Figure 3. Methods for calculating thinning rates between hypothetical graphic log locations 1 and 2. A) Lobe planview, with 2 graphic log locations and three cross sections representing the oblique orientation of the Point Loma outcrop with respect to paleoflow (A-A’), as well as true strike-parallel (B-B’), and dip parallel (C-C’, aligned to 304° paleoflow) projections. B) The only thinning rate that can be accurately measured is the oblique thinning rate (A-A’) using the known distance between graphic logs 1 and 2 and the associated bed thickness. The strike- and dip-parallel thinning rates would assume a thickness, as there is no outcrop at that location. Thus, we did not adjust any measurements for paleocurrent orientation because of the lack of data in the projected strike or dip orientation.

Figure 4. Photographs of Point Loma Formation exposures at Cabrillo National Monument (courtesy of California Coastline Project). (A) Overview photograph, showing the layout of the ‘tidepools’ area. Note that only ~ 10 m of the Point Loma is exposed here, between the ocean and Quaternary alluvium. (B) Photograph (top) and interpretation (bottom) of submarine lobe element (LE) architecture. Also note the location of graphic logs S1-13 and MS1-6.

Figure 5. Uninterpreted (top) and interpreted (bottom) orthomosaic of Area 1 (northern area) derived from a digital outcrop model. Sparse data was collected from Lobe element One (purple) due to poor exposure. Element Two (yellow) is well exposed, with beds thinning to the north and megaflutes erode the uppermost bed. Elements Three (green) and Four (blue) are well exposed along the upper cliff, and beds are traceable southward into Area 2 (Fig. 6). Note the location of Fig. 9, where detailed graphic logs (MS1-MS6) were measured to constrain event-bed thickness changes over a short (~ 15 m) lateral distance.
Figure 6. Uninterpreted (top) and interpreted (bottom) orthomosaic of Area 2 (southern area) derived from a digital outcrop model. Note the apparent onlapping geometry of Element Two (yellow) onto Element One (purple; see detail in Fig. 9). Elements Three and Four are more laterally continuous, but outcrop exposure is lost to the south due to modern erosion.

Figure 7. (A) Correlation panel of the study area (see Fig. 1, 4 for locations of graphic logs). Note the abrupt thinning and onlap of Element Two (yellow) from north to south, whereas other elements are more laterally continuous. (B) Sandstone net-to-gross variability among lobe elements. Element Two displays decreasing net-to-gross values in both directions from S8, whereas other elements show inconsistent or more complicated lateral trends. For detailed graphic-log data, see Supplementary Figure 1.

Figure 8. Log “S6”, with (A) detailed graphic log with sedimentary structures, and (B), sand-bed thickness organised by bed number, with bed 1 being the basal logged sand bed. Using only this one-dimensional (1D) data, constraining the element boundaries (e.g., Element Three to Four) that are apparent using the lateral outcrop data would be difficult. This suggests that bed thickness alone may not be a diagnostic criterion for recognising lobe elements in subsurface core/well-log data. See location of S6 in Figures 4, 6, 7.

Figure 9. Compensational stacking: (A) Inter-element compensation (Element One to Element Two) with internal intra-element compensation of event-beds in Element Two (beds marked A–G). Plot (B) contains bed thickness (m) on the left axis, thinning rate (cm/m) on the right axis in red, distance (m) on the bottom axis with graphic log locations marked with open circles. Note the compensational bed stacking displayed by beds A–G.

Figure 10. Area 1 detailed event-bed correlations. (A) Outcrop photograph (top) and correlation panel (bottom) with colours indicating lobe elements from Figure 7. (B) Plot of lateral changes in thickness and thinning rate for eight sandstone beds. Graphic log locations marked with open circles. Bed compensation occurs within Element Three, predominantly in beds thicker than 10 cm (e.g., J, K, L).

Figure 11. Event-bed parameters for the four lobe elements at Cabrillo National Monument. (A) Sandstone bed and mudstone interval geometries displayed as a single polygon for each element (sand and mud data shown separately in parts B and C). Note that Element Two (yellow polygon) has slightly thicker beds with higher thinning rates than other elements. (B) Kernel density estimates of thickness and thinning rate distributions for sandstone bed and mudstone intervals. The differences are quite subtle, and a K-S Test shows that only Element Two is distinguishable in sand bed thickness and Element Four in mud interval thickness. Thinning rates are not statistically distinguishable among the four lobe elements. (C) Sandstone bed thickness vs. fining rate (i.e., how fast grain size changes laterally). No clear trend between the four lobe elements is apparent. In part C, psi = log2[grain size in mm]). In parts A and C, coloured dot is the median value, and the polygon is the 90% volume contour (i.e. a polygon that encompasses 90% of the data).

Figure 12. Event-bed parameters for the Point Loma Formation compared to the database developed by Fryer and Jobe (2019). In parts (A) and (B), the entire Point Loma dataset (sandstone bed and mudstone interval geometries) are displayed as a single polygon in comparison to all depositional environments (A) and lobe sub-environments (B). (C) and (D) are kernel density estimates of thickness and thinning.
rate distributions for sandstone bed (yellow) and mudstone intervals (grey). Generally, the Point Loma has thickness and architecture most similar to other lobe deposits, as shown in (A) and (C). Parts (B) and (D) demonstrate that the Point Loma has geometries most similar to semi-confined distal lobe deposits (as defined by Fryer and Jobe, 2019).

Supplemental Figure 1. Correlation Panel of the Point Loma Formation at Cabrillo National Monument, with detailed sedimentary structures for graphic logs and bed correlations.
| Name | Description | Bioturbation | Image |
|------|-------------|--------------|-------|
| (A)  | Single turbidite sandstone bed | 3-30 cm thick. Light brown to tan, lower fine to lower medium base, fining upwards with Bouma sequence structures, commonly massive (Ta) to parallel laminated (Tb) to ripple laminated (Tc) with an erosive to loaded base. | Vertical and horizontal burrows that occasionally cut through the full thickness of one bed (Ophiomorpha). |
| (B)  | Mudstone intervals | 1-10 cm thick. Grey mudstone units with consistent lateral thickness. Commonly show faint wavy to parallel-laminated lenses of silt less than 5mm thick. Interpreted as Bouma Td and Tc units of one event-bed, but may represent multiple events. | Small (<15mm) dark grey burrows (Chondrites) and large (>1cm) sand and mud-filled burrows (Ophiomorpha). |
| (C)  | Amalgamated turbidite sandstone bedsets | 10-50 cm thick. Very similar to (A) above, but with amalgamation surfaces, commonly with laterally continuous flame structures. Only some of these bedsets show coarsening of grain size across bed boundary. | Vertical and horizontal sand and mud-filled burrows (Ophiomorpha) found at bed tops. |
| (D)  | Hybrid-event bed (Bed “L” in Fig. 10) | 5-40 cm thick. Light brown to dark grey, showing lateral transition between bed type (A) to a bed with high clay matrix and contorted sand laminae. Locally contains abundant organic matter, mud clasts, concretions < 5 cm and internal truncation features. Lateral facies transitions are abrupt (< 5 m). | Bioturbation contained within the upper ~3cm of the event-bed, usually small (<5mm) mud-filled burrows (Chondrites). |
| (E)  | Mica rich turbidite sand with recessive mudstone cap (datum used in Fig. 7) | 6-40 cm thick. Light grey, parallel to ripple laminated, fine to medium biotite-rich sand with an erosive base. Very distinctive and laterally continuous. Upper portion is brown mudstone with abundant sheared vertical and horizontal calcite veins. | No bioturbation identified. |
**A**

Unconstrained lobe dimensions (due to limited outcrop exposure)

Depositional Strike (projected)

Depositional Dip (projected)

Outcrop orientation (oblique to paleoflow)

**B**

Thinning rate = \( \frac{\delta \text{thickness}}{\delta \text{distance}} \)

Known Thickness

A Loc. 1 Known thinning rate A' Loc. 2 Known Thickness

B Loc. 1 Unknown thinning rate B' ? Unknown Projected Thickness

C Loc. 1 Unknown thinning rate C' ? Unknown Projected Thickness

Known Distance

Known Distance

Known Distance
