PS Facies Architecture Analysis and Modelling of the Sandy Slope Channel Fills at San Clemente, California*

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Search and Discovery Article #51128 (2015)**
Posted August 24, 2015

*Adapted from poster presentation given at AAPG 2015 Annual Convention and Exhibition, Denver, Colorado, May 31 – June 3, 2015

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Abstract

Sandy slope channel fills can form important hydrocarbon reservoirs, but significant uncertainties exist concerning reservoir architecture. The outcrop of the Miocene-Pliocene Capistrano Formation at San Clemente exposes a ca. 800 m long, 15 m-thick succession of sand dominated slope channel fills. This provides a good case study for us to reconstruct and model facies and associated reservoir architecture based on paleocurrent data, sedimentary logs and large-scale photomosaics collected in the field. The succession at San Clemente represents an oblique section through a large slope channel system composed of 10 channel fills. The laterally relatively continuous exposure reveals channel axis (thick-bedded coarse sand and/or gravels), off-axis (thick/medium bedded coarse sand alternating with thin-bedded turbidites) and channel margin (thin-bedded turbidites and/or siltstone drapes) sub-environments from different channels. Because these sub-environments represent deeper, intermediate and shallower parts of these channels respectively, channel lateral and vertical migration history and resultant overall architecture can be reconstructed using exposed sub-environments within each channel based on the assumption that the 10 channels are similar in their dimensions and facies distribution from channel axis to channel margin. It is believed that the outcrop observed at San Clemente is a result of channel lateral migration and vertical aggradation and degradation rather than just lateral migration or vertical aggradation, and is partly comparable to the modern Lucia Chica channel system, offshore California. Building on this conceptual model, the probabilities of different facies transitions can be modelled and then used to predict the facies architecture at bed, bedset and channel scale. The results show that we can reasonably reproduce the facies architecture observed in outcrop with vertical conditioning data (sedimentary logs or well logs calibrated to core). The transition statistics and conceptual model used in this study can therefore be used as constraints for facies and reservoir architecture modelling in comparable slope channel systems in the subsurface.

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AAPG Annual Convention & Exhibition 2015 with SEPM (Society for Sedimentary Geology)

PRACSS Predicting Reservoir Architecture in Channelized Slope Settings

1. Introduction

The well-exposed late Miocene-Pliocene Capistrano Formation at San Clemente, California represents sand dominated slope channel fills that are incised into the muddy slope deposits of the Monterey Formation. The channel fills are composed of coarse to very fine grained sandstones, heterolithics, mudstones and minor conglomerates. Digital mapping, photomosaic interpretation and sedimentary logs reveal that the exposed turbidte channel fills at San Clemente represent only a slice of a much bigger channel system, which consists of a number of channels that migrate laterally and vertically.

This study focuses on characterization and simulation of facies architectures of the exposed channel fills using facies transition probability analysis.

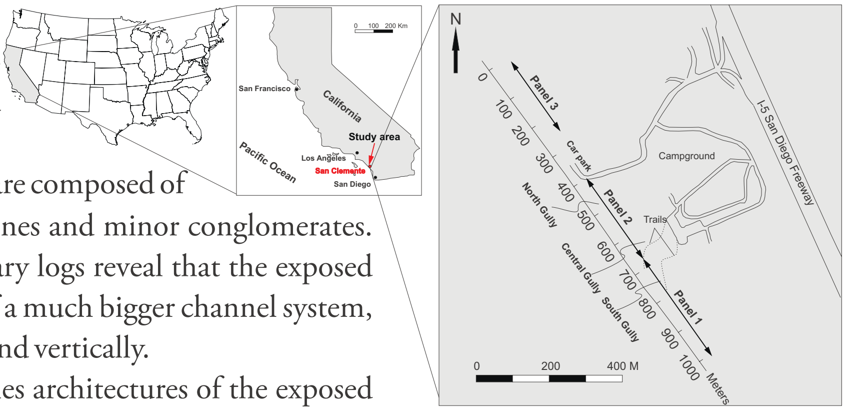


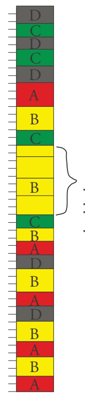
Figure 1. Location of the study area. The main exposure (sections A, B,C) of the late Miocene-Pliocene Capistrano Formation is highlighted.

2. Methodology

Facies transition probability analysis is used to investigate vertical facies sequences and to simulate 3D facies architectures.

Vertical facies sequences are analysed to test if there is any vertical trend related to distinct architectural elements based on vertical facies transition probabilities. Facies architecture simulation is undertaken to reproduce the 3D facies distribution based on facies proportions, transition probabilities and mean length in 3 dimensions collected from measurements or geological conceptual models.

2.1 Vertical facies sequence analysis



	A	B	C	D
A	—	4	0	1
B	2	—	1	2
C	0	2	—	2
D	2	0	2	—

Transition count matrix

	A	B	C	D
A	—	80%	0	20%
B	40%	—	20%	40%
C	0	50%	—	50%
D	50%	0	50%	—

Transition probability matrix

Random transition probability matrix
estimated using an iterative solution
(Powers & Easterling 1982)

Difference matrix
(transition probability matrix minus random transition probability matrix)

Vertical facies transition diagram
(defined by positive values in difference matrix that pass tests for randomness at a selected significance level)

Figure2.1 Diagrams showing the extraction of transition properties from a hypothetical sedimentary log with 4 facies (A, B, C, D) (modified from Doveton, 1971) and workflow of vertical facies transition analysis.

2.2 Facies architecture simulation

Categorization (facies assemblage classification)
Detailed facies classification used in vertical facies sequence analysis need to be upscaled in order to form facies assemblages with reasonable geological continuity

Model data collection
Facies assemblage thickness and lateral continuity, proportions, juxtapositional tendencies (transition probabilities) calculated from the outcrops or from geological conceptual models

3D Markov chain model
Build vertical and lateral Markov chain model on the basis of collected data.
Interpolate Markov chain model in other directions

Conditional simulation(two steps)
Cokringing-based SIS;
Simulated quenching (Carle and Fogg, 1998)

3. Facies and facies assemblages

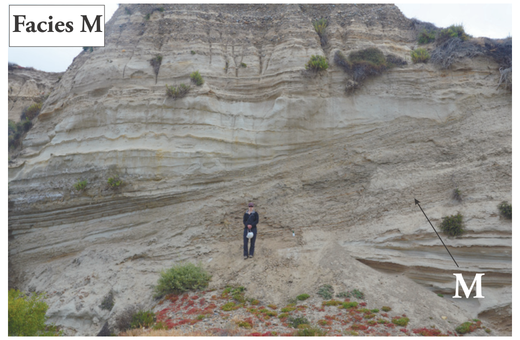
Facies and facies assemblage classification is the basis for vertical facies transition probability analysis and 3D facies architecture simulation. Vertical facies sequence analysis uses detailed facies classifications while facies architecture simulation uses relatively simple facies assemblages (upscaled detailed facies) to constrain reasonable lateral continuity.

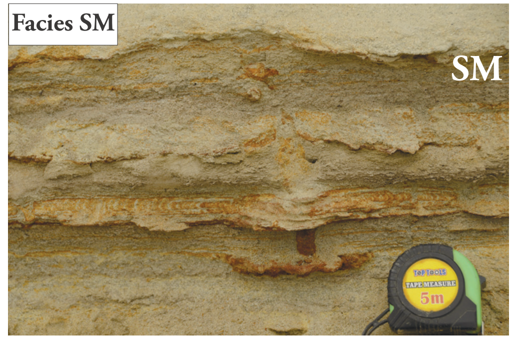
In this study, facies and facies assemblages are defined mainly based upon their abundance and lateral continuity and principal sedimentary characteristics (grain size, grading and sedimentary structures).

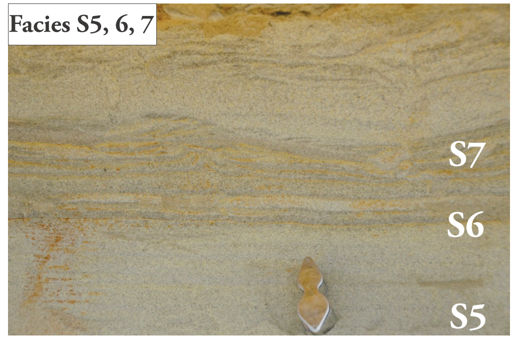
Facies	Sketch	Sedimentary characteristics	Bedding patterns	Depositional processes	Depositional environments
M		**Mudstones** silty or sandy mudstone/siltstone, usually strongly bioturbated	Wedging and drape onto erosion surfaces	Low density turbidity currents	Channel margin
SM		**Heterolithics** Siltstone dominated interbedded siltstone/mudstone and fine to medium grained sandstone; usually	Tabular and laterally continuous, no amalgamation	Low density turbidity currents	Channel margin to channel off axis
S7		**Ripple laminated sandstones** very fine to medium grained, ripple laminated, mainly thin bedded	Tabular or wedging, laterally continuous, rare amalgamation	Low density turbidity currents	Channel axis to channel margin
S6		**Parallel laminated sandstones** very fine to medium grained, parallel laminated, mainly thin bedded	Tabular or wedging, laterally continuous, rare amalgamation	Low density turbidity currents	Channel axis to channel margin
S5		**Graded fine grained sandstones** fine to medium grained, mainly massive, normally graded, thin to medium bedded	Tabular or wedging, laterally continuous, rare amalgamation	Low density turbidity currents	Channel axis to channel margin
S4		**Graded coarse grained sandstones** medium to coarse-very coarse grained, mainly massive, normally graded, medium to thick bedded	Tabular, laterally continuous, common amalgamation	High density turbidity currents	Channel axis to channel off axis
S3		**Pebbly sandstones** pebbles to coarse grained sandstones, typically massive, coarse-tail graded, medium to thick bedded	Tabular, laterally continuous, common amalgamation	High density turbidity currents	Channel axis to channel off axis
S2		**Mudclast breccias, sandy** typically massive, ungraded, usually aligned into layers	Lenticular, discontinuous, rare amalgamation	Turbidity currents/ debris flows	Channel axis and channel margin
S1		**Mudclast breccias, conglomeratic** typically massive, ungraded, disorganized	Lenticular, discontinuous, rare amalgamation	Turbidity currents/ debris flows	Channel axis and channel margin
G		**Conglomerates** clast supported granules to cobbles with rare boulders, usually normally graded	Lenticular, discontinuous, common amalgamation	High density turbidity currents	Channel axis
E		**Erosional surfaces** erosional depth >10cm; a special facies for vertical facies sequence analysis due to its abundance in channel axis			Channel axis to Channel off axis

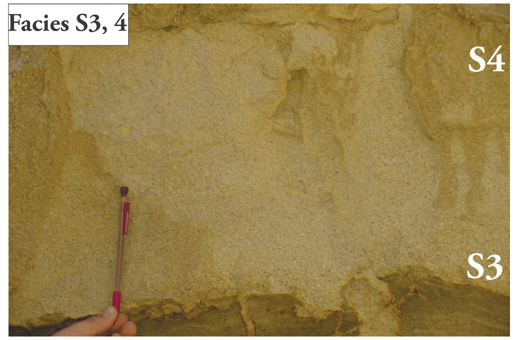
Table 1. Summary of the facies and facies assemblage in the turbidite channel fills at San Clemente, showing their main sedimentary characteristics, bedding patterns, depositional processes and depositional environments.

Facies examples









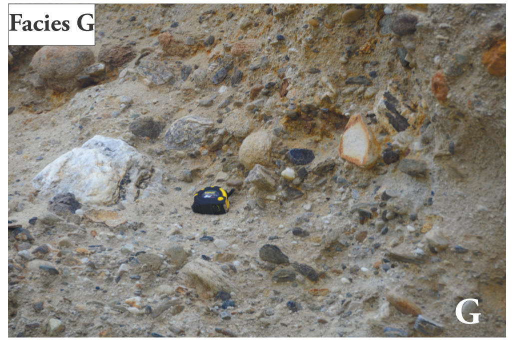


Figure 3. Typical sedimentary facies from the turbidite channel fills at San Clemente, California (see table 1 for the detailed description of their sedimentary characteristics, bedding patterns, depositional processes and associated depositional environments).

4. Facies distribution in outcrop

- Facies distributions of the turbidite channel fills at San Clemente are mapped out based on high-resolution photomosaic, field sketches and 31 sedimentary logs
- Coupled with the mapped big erosional surfaces, facies distributions are used to analyse and reconstruct the turbidite channel architectures; they also serve as geological models for vertical facies sequence analysis and 3D facies architecture simulation

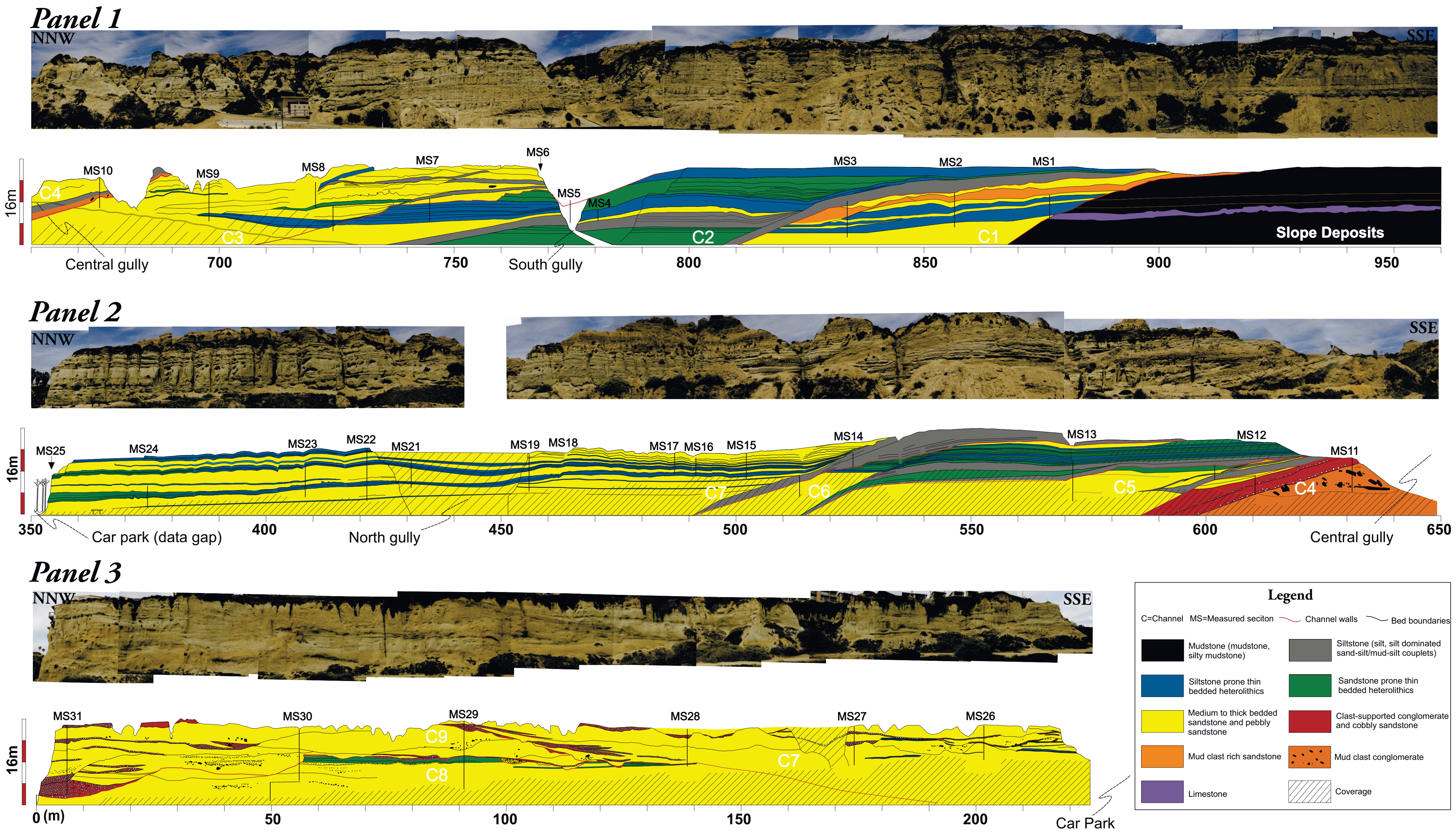


Figure 4. Photomosaic and line interpretation of the outcrop showing the distributions of facies assoications and channels (see figure 1 for the location of panels). Most of the channels are draped by siltstone/sand-silt couplets at channel margins. They tend to be replaced by interbedded sandstones and mudstones toward channel axis, which in turn, are replaced by coarser grained facies such as thick bedded massive sandstones and pebbly sandstones. The changes in facies trends correspond to changes in architectural elements. This general trend serves as a simple test of the results from vertical facies sequence analysis and 3D facies architecture simulation.

5. Channel architecture interpretation

- The outcrops at San Clemente represent only a slice of a much bigger channel system
- Architecture of the whole channel system is reconstructed based on facies distribution and erosion surface geometries.

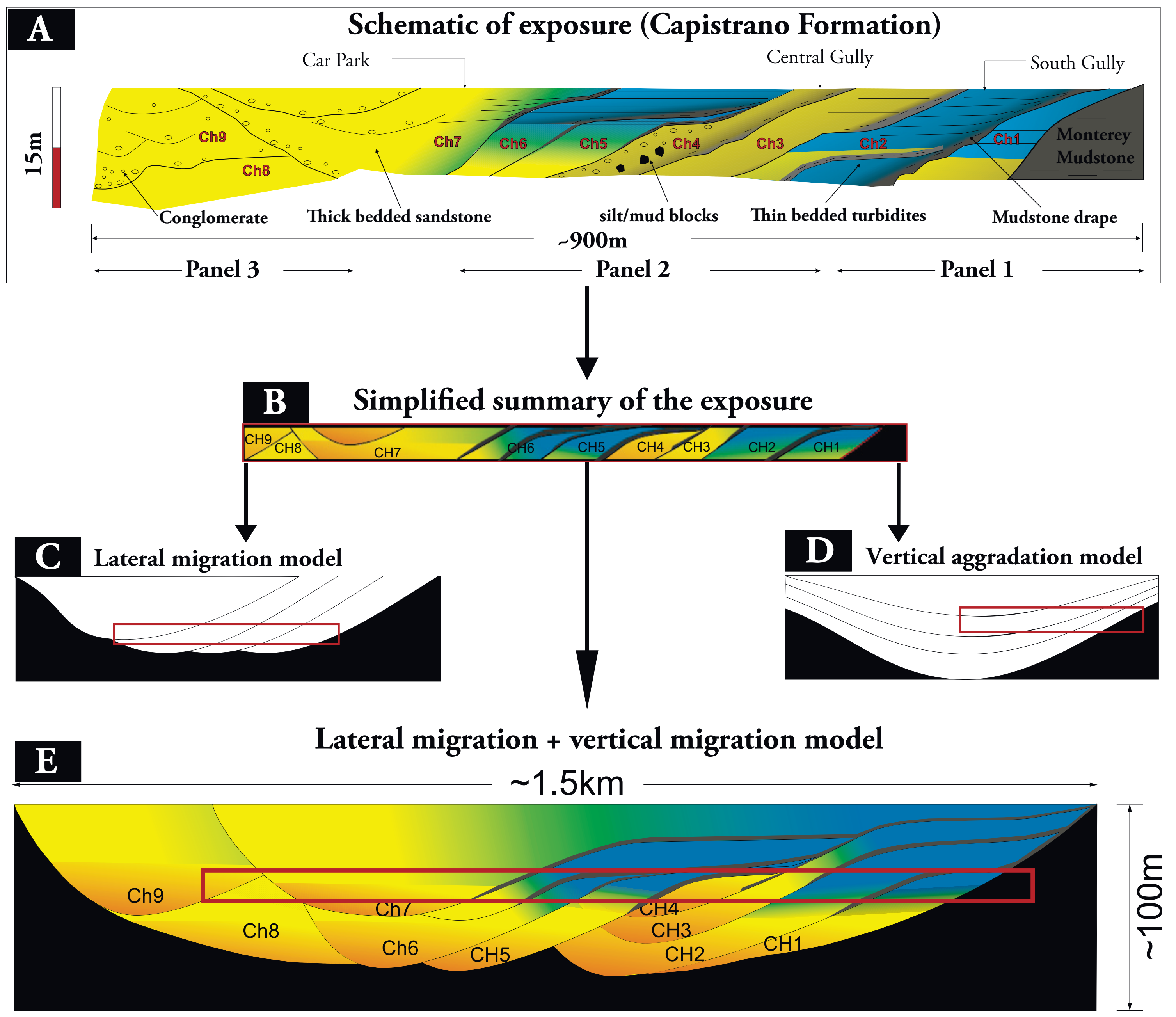


Figure 5A Field sketch of the outcrops showing the main facies association distribution; Figure 5B Simplified summary of the outcrops showing the spatial distribution of the main channel cuts and dominant facies associations; Figure 5C and 5D Two end members of architectural models (lateral migration versus vertical aggradation) for the whole channel system; Figure 5E the proposed channel architectural model in this study based on detailed facies distribution analysis, mapping and projection of the erosional surfaces.

6. Vertical facies sequence analysis

Specific architectural elements can be identified in outcrop where their 2D or 3D architecture are visible. At San Clemente, three distinctive channel architectural elements are recognized, i.e., channel axis, channel off-axis and channel margin based on 2D bedding patterns and geometries. Vertical facies transition analysis are undertaken for each of these architectural elements in order to develop typical vertical facies sequences for architectural elements prediction where there is only 1D data (vertical successions such as wireline logs and/or core data) are available.

6.1 Generalized nature of channel axis to channel margin deposits

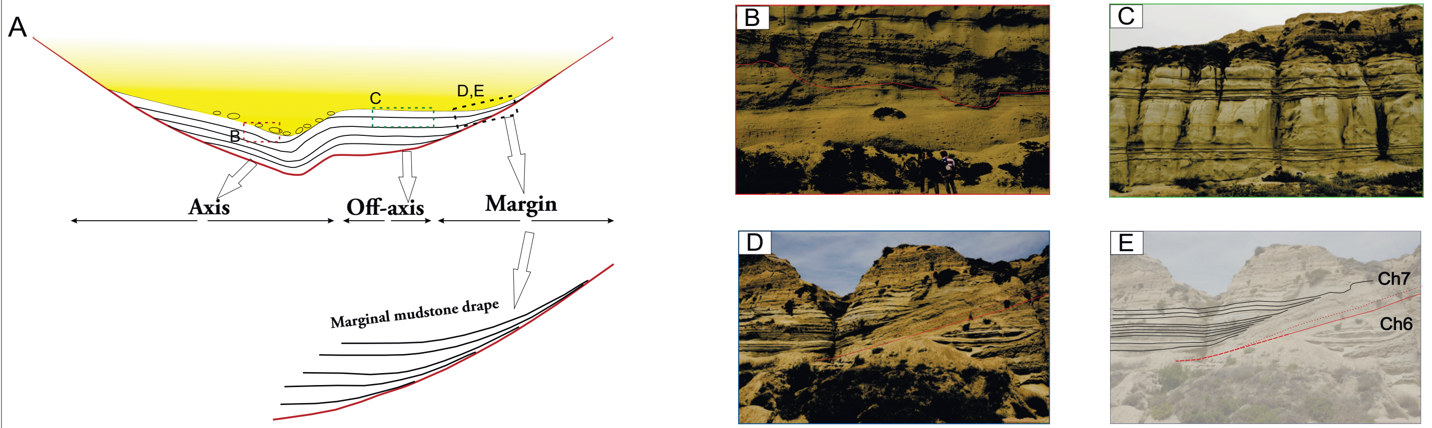
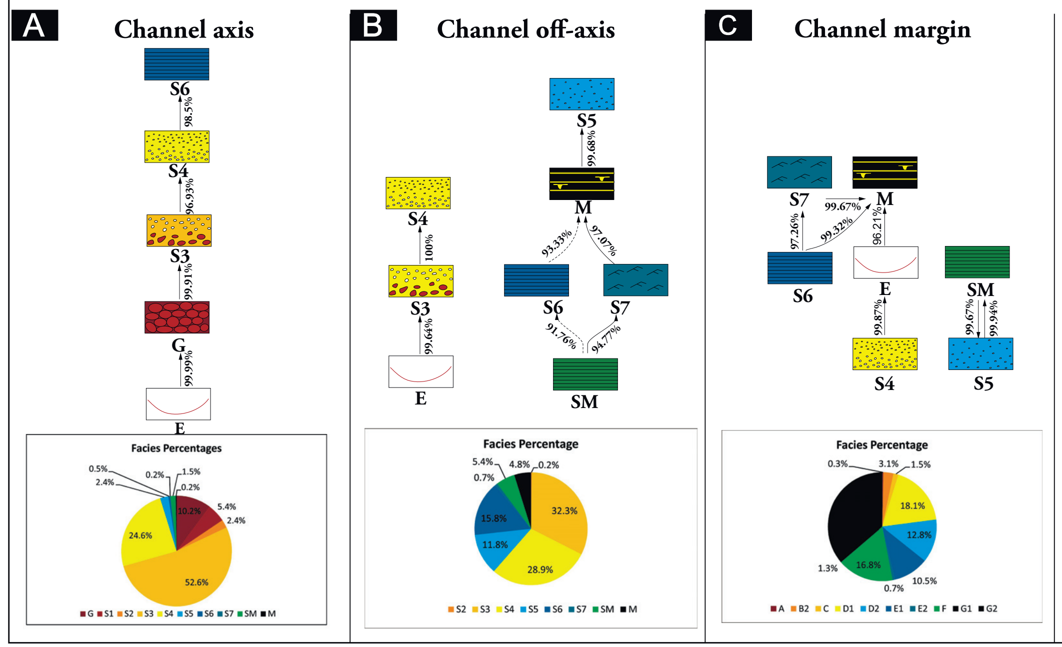


Figure 6.1A Generalized relationship of channel axis to channel margin deposits showing the amalgamation/erosion dominated nature of channel axial sands and their lateral equivalence of mudstone drapes deposited as a result of turbidity current density stratification. Figure 6.1B-E Outcrop features of channel axis to channel margin deposits.

6.2 Vertical facies sequences and facies percentages for different architectural elements



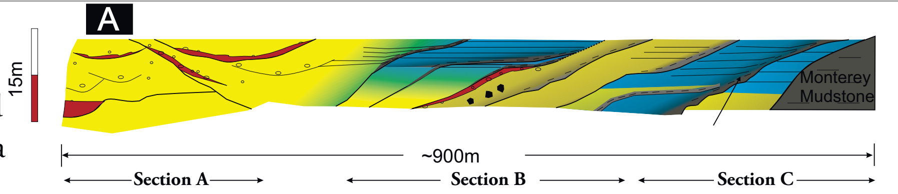
- Figure 6.2A, B, C showing the vertical facies transition probabilities and facies percentages at channel axis, channel off-axis and channel margin, respectively.
- Both facies transitions and facies percentages show distinctive trends. They can serve as a predictor in a new and comparable situation and can provide significant insights into hydrodynamic processes.

7. Facies architecture simulation

A variety of approaches are available for facies architecture simulation, such as MPS, object-based modelling. In this study, facies architectures are simulated via facies transition/Markov Chain model (see section 2.2).
Compared to some other simulation techniques, this approach is conducive to incorporation of soft geological information, such as, lateral facies continuity from other comparable analogues or from direct measurement.

Geological model

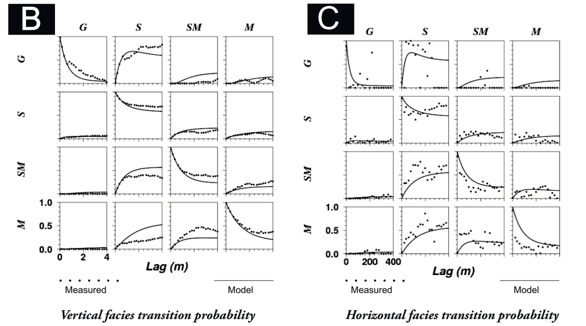
The geological model (firgue 7A and photomosaic in figure 4 A, B and C) is used to validate simulation results and model data collection.



Models of spatial variability

Models of spatial variability (facies assemblage spatial variability in this case) are built based on Markov chain models. Mathematically, a Markov chain model assumes a matrix exponential form (Carle and Fogg, 1998; see figure B and C).

Overall, the Markov chain model shows a good fit to the measured data vertical sedimentary logs and 2D photomosaics.



Conditional simulation

what can be reproduced:

- Sandier and coarse facies trends towards section A in outcrop (the left on the XZ face of figures 7D-7G);
- Some big cutting erosional surfaces such as Channel 2 and channel 3 confining surfaces;
- Thinning and onlapping of bed packages at channel 7 margin(X is between 300 to 500 in X on the XZ face of firgues 7D-7G)

What cannot be reproduced:

- Closely spaced erosion surfaces (Ch4-7 cutting surfaces) without

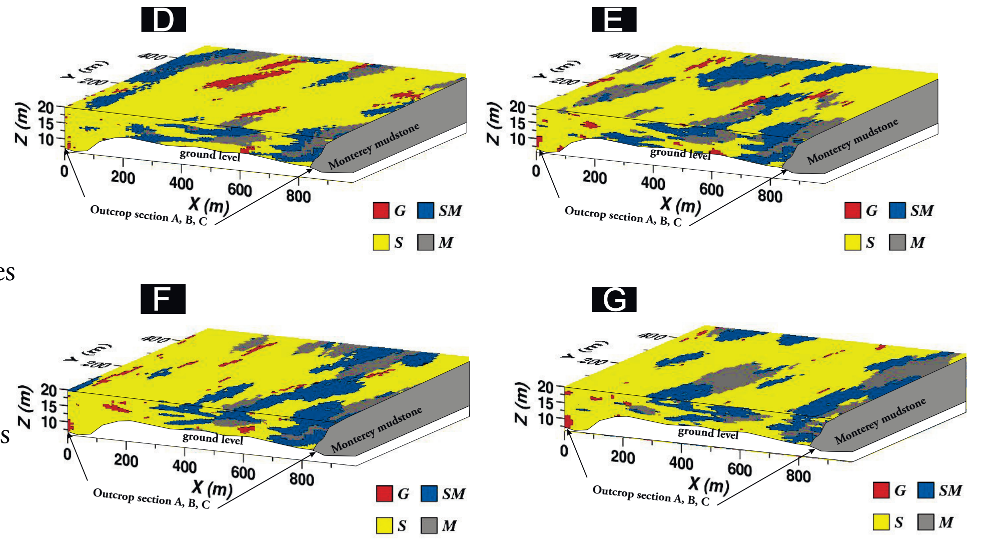


Figure 7D-E. Four of the 100 conditional simulations. The XZ face in those stimulations corresponds to sections A, B and C in outcrop, i.e., the geological model used. The contact between Monterey mudstone and the outcrops under study is defined deterministically. G, S, SM and M represent the four facies assemblages: conglomerate, sandstone, heterolithics and mudstone.

8. Conclusions

- The exposed turbidte system at San Clemente probably represents only part of a much large channel system.
- The channel stacking patterns are interpreted as a result of a combination of punctuated lateral and vertical migrations.
- Three distinct architectural elements within channels can be identified in outcrop-channel axis, off-axis and margin. Vertical facies transition analysis shows that these architectural elements can be characterized by different vertical facies sequences and facies percentages.
- Facies architecture simulation study demonstrates that 2D or even 3D facies architecture can be partially reproduced, but closely spaced erosion surfaces cannot be reproduced properly without enough conditioning data.
- Reservoir heterogeneities in turbidite channels at sub-seismic scale can be partially characterized and predicted via vertical facies sequence analysis and facies architecture simulation based on vertical successions, such as wireline logs, but it should be noted that heterogeneities can be underestimated greatly in the subsurface.

Acknowledgements

PetroChina bp DONG energy TULLOW RWE Statoil

References

Ingle, J. C., 1971, Paleoecologic and paleobathymetric history of the late Miocene–Pliocene Capistrano Formation, Dana Point area, Orange County, California, in F. W. Bergen, ed., Geologic guide book Newport Lagoon to San Clemente, Orange County, California: coastal exposures of Miocene and early Pliocene rocks: Pacific Section SEPM, p. 71–88.

Walker, R. G., 1975, Nested submarine-fan channels in the Cap- istrano Formation, San Clemente, California: GSA Bulletin, v. 86, n. 7, p. 915-924.

Clark, J. D., and K. T. Pickering, 1996, Submarine channels processes and architecture: London, Vallis-Press, 231 p.

Carle SF, Labolle EM, Weissmann GS, Van Brocklin D, Fogg GE (1998) Conditional simulation of hydrofacies architecture: a transition probability/Markov approach. In: Fraser GS, Davis JM (eds) Hydrogeologic models of sedimentary aquifers. Special Publication, Concepts in Hydrogeology and Envi- ronmental Geology, SEPM, Tulsa, OK, pp 147–170.

Camacho, H., Busby, C.J. and Kneller, B.C. (2002) A new depositional model for the classical turbidite locality at San Clemente State Beach, California. Am. Assoc. Petrol. Geol. Bull., 86, 1543–1560.

Campion, K. M., A. R. Sprague, D. Mohrig, R. W. Lovell, P. A. Drzewiecki, M. D. Sullivan, J. A. Ardill, G. N. Jensen, and D. K. Sickafoose, 2000, Outcrop expression of confined chan- nel complexes, in P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, and D. T. Lawrence, eds., Deep water reservoirs of the world: Houston, Gulf Coast Section SEPM Foundation, p. 127–150.

Campion, K.M., Sprague, A.R., Sullivan, M.D., 2005. Field Guidebook for the Annual Fall Fieldtrip. Pacific Section of the SEPM, San Clemente, California.