Abstract

Viewed within a dynamic 3D accommodation perspective, petrophysical log motifs of 113 wells in the adjoining Captain Lucey and Richard King fields of Jim Wells and Nueces counties, South Texas, reveal the overprint of fourth-order autocyclic processes of regression and transgression within a general third-order allocyclic sea level fall. Five reservoir sand environmental assemblages sealed by transgressive systems tract (TST) shales identified within the clastic shelf wedge of the Oligocene-Miocene Frio Formation are: lowstand systems tract (LST) delta 1, regressive systems tract (RST) to LST delta plain distributaries, RST—LST distributary crevasse splay, TST barrier island, and LST—RST delta 2.

Production decline curve analysis (PDCA) of 18 reservoirs in 12 of 20 currently active wells of these two fields demonstrate a systematic relationship between reservoir elements and their associated depositional environments. The deltaic 1 and deltaic 2 environments (delta front sands) have the best reservoir quality sands of the five, exhibiting linear lowest decline rates with the highest average flow permeabilities (80 md) and largest drainage areas (290 ac). A close second in drainage area (214 ac) is the barrier island sand with lower average flow permeability (7 md). The fluvial sand exhibits the highest decline rates with good drainage area (214 ac) and modest average permeability (32 md). The poorest reservoir quality is the crevasse splay sand with rapidly declining rates, lowest average permeability (1 md) and smallest drainage area (110 ac).

The strong relationships between PDCA and depositional environments in these South Texas Frio Formation sands point to the potential applicability of PDCA–depositional facies linkages as a reservoir performance predictor in fields elsewhere.


CLASTIC FACIES RESERVOIR CHARACTERIZATION IN A SEQUENCE STRATIGRAPHIC FRAMEWORK THROUGH PRODUCTION DECLINE CURVE ANALYSIS: EXAMPLE-FRIO FORMATION, SOUTH TEXAS

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Problem Definition: A Question of a priori vs. a posteriori

In a mature field, do we now have all the answers to our questions, or indeed, have all of our questions been answered?
Problem Definition: A Question of Apriori vs. A posteriori

Or have we missed something? Or to put it another way, can a mature field provide new insight into optimizing exploitation in “look-alikes”, or “step-outs”, or even in missed “behind-pipe” pay?

Is it a sunrise or a sunset on the production?
Problem Definition: The Tool

PDCA

From a petroleum engineering perspective, PDCA is a fundamental tool for examining well performance, forecasting future production, and determining value of the producing asset.

Type Production Curve: F.L. Blundell 4

Bubble Point

(Gas Production > Oil Production)

GAS PRODUCTION IN RED, OIL PRODUCTION IN GREEN
IS THERE A GEOLOGICAL PERSPECTIVE? That is, can Production Decline Curve Analysis (PDCA) provide geologically useful information, e.g. reservoir characterization that can assist our exploitation?

THE STRATEGY:
Find a laboratory
Find isolated reservoirs in the laboratory (in a sequence stratigraphic sense)
Find field data PDCA
Investigate
The Laboratory

South Texas

Study Area
The 113 wells of Captain Lucey and Richard King fields in Jim Wells and Nueces Counties of South Texas.
Gulf of Mexico Coastal Plain major oil and gas producing units juxtaposed with the eustatic sea-level curve (modified from Swanson et al., 2007 and Haq and Al-Qahatani, 2005). Gas (red triangle) and oil (green circle) columns refer to regionally producing reservoirs.
Regional NW-SE cross section of Central Texas illustrating the early Cretaceous to the present day shelf margin (modified from Swanson et al., 2007).
The Sequence Dilemma

Finding a reservoir with geometrically sealed (four-way closure) within shales is facilitated by 3D seismic. But how does one find a sequence stratigraphic-sealed reservoir from petrophysics? Certainly, we can use the wireline log motifs to indicate vertical changes in depositional energy...
One can also describe motifs of depositional motif tendencies from the logs and with geometry establish the depositional environment, e.g. Fisher, 1969; Galloway and Hobday, 1983; Holtz and McRae, 1995.
As vertical facies relationships are sensitive both to extrabasinal caused bathymetric changes and to intrabasinal caused changes in process energy, the dilemma becomes: Does the wireline log coarsening-upward shown a progradation (regression) or a sea level fall? Does a fining upward reveal a retrogradation (transgression) or a sea level rise?
The Sequence Dilemma

But how does one differentiate vertical (allocyclic\(^1\)) from lateral (autocyclic\(^2\)) processes from the petrophysical character?

\(^1\)allocyclic – extrabasinal, chiefly affected by global tectono-eustatic changes in sea level

\(^2\)autocyclic – intrabasinal, chiefly affected by local depositional processes
The operational cognitive bias:

1. As allocyclic unconformities commonly exhibit acoustic impedance contrasts, such time significant horizons are facilitated by seismic interpretation regionally...The classic “Vail” approach with a vertical bias.

2. As autocyclic flooding surfaces are often accompanied by the deposition of fine-grained (low energy) deposits over coarser-grained (high energy) deposits, these are locally readily identified and correlated on wireline logs...The classic “Galloway” approach with a horizontal bias.
The key to answering this dilemma lies in combining these two words: regional (allocyclic) vs. local (autocyclic), as it is the GEOMETRY of filled space, the sedimentary record, which provides the answer: the a posteriori observable record of the potential space that was made available or unavailable for sediment accumulation.
Allocyclic sea-level curve for one complete sea level cycle with associated vertical accommodation changes. The descending limb of the curve defines the falling stage of sea level and the ascending limb of the curve defines the rising stage of the sea level. Blue indicates HST, Yellow RST, Red LST, and Green TST (adapted from Pigott and Abdel-Fattah, 2014).
ALLOCYCLIC STILLSTAND, abundant autocyclic sediment supply provides toplapping progradation which results in a decrease in the available horizontal space recorded by a regression indicated in brown.
ALLOCYCLIC GLOBAL SEA LEVEL RISE with an accompanying increase in both horizontal and vertical space but with weak autocyclic sediment input is recorded by a horizontal onlapping transgression with uplapping and upstepping vertical coastal aggradation indicated in green.
ALLOCYCLIC GLOBAL SEA LEVEL RISE accompanies strong fluvial system input relative to marine sediment redistribution processes. Coastal aggradation and progradation indicated in blue fills the available vertical and horizontal space.
ALLOCYCLIC GLOBAL SEA LEVEL FALL TO GLOBAL LOWSTAND with strong autocyclic input. Decrease in both horizontal and vertical space is recorded by a dip oriented black unconformity truncating underlying strata with downlapping and downstepping progradation indicated by thin yellow units which culminate in lowstand regressive deposits indicated in brown.
RELATIVE SEA LEVEL FALL TO LOWSTAND with strong autocyclic input caused by accompanying autocyclic intrabasinal uplift.
3D Accommodation

STATIONARY SHORELINE with vertical and horizontal accommodation stasis.
To discriminate the allocyclic-autocyclic process, one must establish the 3D accommodation geometry; the nature of the fill or removal of sedimentary facies confirms the geometry.
From an allocyclic (global eustatic) perspective, Frio deposition (indicated by the blue arrow) occurred during a Chattian second order global sea level fall with three minor apexes of third order high sea levels which give way to a third order Aquitanian sea level rise.
Recall the structural setting: the shelf is foundering during the Chattean, thus a reinforcing relative sea level rise to the global sea level rise. If any regressions are indicated, they must be owing to autocyclic processes.
Dominating autocyclic responses observed on for field-representative SP log of the F.L. Blundell 4. Three third-order responses identified, and seven fourth-order responses identified. From bottom to top, the colored lines indicate the picked marker bed positions of environment boundaries.
Thus the Frio wedge relative sea level is represented by a foundering shelf with cycles of global sea level rise and fall but with pulses of enormous clastic autocyclic input providing sands encapsulated in shales.
The curved black line schematically represents the Frio depositional facies as an evolutionary and cumulative response to both autocyclic and allocyclic processes. Time axis orthogonal to the plane of accommodation drivers.
Paleoenvironments

PLATE I: A-A' Stratigraphic Cross Section
Datum: Het C

Strike cross section hung on transgressive Heterostegina C.
PLATE III: F-F' Stratigraphic Cross Section

Datum: Het C

Dip cross section hung on transgressive Heterostegina C.
Lower Chattian Norias Delta sands of the Frio showing three delta lobes. Sand thicknesses: max 578 ft, min 251 ft, mean 364 ft.
Mid Chattian RST to LST Frio sands of the Gueydan Fluvial System deposited during sea level fall in incised topographic low of preceding Deltaic I Environment. Sand thicknesses: Max 862 ft, Min 108 ft, and Mean 368 ft.
Late Chattian fluvial associated crevasse splay Frio sands with thicknesses:
Max 443 ft, Min 36 ft, Mean 143 ft.
Early Aquitanian Anahuac sands of Greta Barrier Island system. Sand thicknesses: Max 489 ft, Min 156 ft, Mean 291 ft.
Mid Aquitanian Anahuac lagoonal storm washover sands associated with Greta Barrier Island. Sand thicknesses: Max 612 ft, Min 89 ft, Mean 295 ft.
Late Aquitanian Norias Delta System with prograding Anahuac sands revealing portions of three main lobes. Sand thicknesses: Max 1402 ft, Min 376 ft, Mean 801 ft.
Post depositional structuring of Frio Fault Zone cuts all facies non-discriminately and enhances field production on structural highs. Suggests faults have high Shale to Gouge ratios.
Major Oligocene-Miocene South Texas Frio depositional systems during one fourth order rising limb in the eustatic Sea Level curve. The autocyclic depositional systems are adjusting to increased vertical and horizontal accommodation.
PDCA CURVES

Curve Types for Decline Curve Analysis

- Exponential Decline: fluid expansion
- Hyperbolic Decline: solution gas drive
- Harmonic Decline: efficient water drive
Decline Curve Variables

- For this field study, the decline curve analysis incorporates both exponential and hyperbolic decline curves for the selected wells in the field study area.

- The following variables described in detail by Poston and Poe (2008) and Foster (2012):

  \[ b = \text{hyperbolic decline exponent} \]

  \[ D_i = \text{initial continuous decline rate} \]

  \[ q_i = \text{initial production rate (start of production)} \]
1. Calculation of $Q_p$ ($Q_p = \text{cumulative production}$) using general hyperbolic decline rate equation

2. Calculation of $q$ ($q = \text{current production rate}$) at a given time determined the method advanced by Fetkovich et al. (1996)

3. Determination of the rate-match point ($q_{Dd}$) and the time-match point ($t_{Dd}$)

4. Rate-match point ($q_{Dd} = \text{rate-match point production}$) and time-match point ($t_{Dd} = \text{time-match point production}$) used to solve for transient flow best fit dimensionless radius ($R_{ed} = \text{transient flow best fit dimensionless radius}$)

5. Calculation of theoretical permeability ($k$) and drainage area ($DA$) via calculations derived by Fetkovich et al. (1996)
Theoretical K and DA Methods

1. Review historical production trends to identify accurate production characteristics for a given depositional environment

2. PDCA for 12 selected wells performed by using PHDWin Integrated Economics and Decline Curve Analysis software

3. Variables derived using PHDWin DCA applied to Fetkovich et al. (1996) decline curve equations in order to characterize a reservoir’s given permeability ($k_{DCA}$) and drainage area ($DA_{DCA}$)
   1. Using the Fetkovich type curve match approach, permeability ($k_{DCA}$) can be solved for from the rate match point equation
   2. The drainage area ($DA_{DCA}$) may then be calculated from rate and time match points

4. Delineation of hydrocarbon producing depositional environments of the 12 wells analyzed and their associated interpreted sequence stratigraphic intervals
Of 20 producing wells, filtering yielded eighteen wells with twelve reservoirs
Historical production curve for the Captain Lucey Field, all wells. Green solid line indicates oil and red dashed line indicates gas.
Historical production curve for the Richard King Field, all wells. Green solid line indicates oil and red dashed line indicates gas.
Production Decline Curve

Well: F.L. Blundell 7
T.D. 6252'
Perf Zone: 5899-5904'
Dep. Environment: Delta Front
Cum Gas: 176 MMCF
Cum Oil: 127 MBBL

q = 32 (11/18/1983), d = 0.09, b = 0.05; K = 45.2 mD, DA = 483 Ac
**Depositional Environment PDCA**

**Production Decline Curve**

Well: F.L. Blundell 8  
T.D. 6180'  
Perf Zone: 3774-3779'  
Cum Gas: 35.6 MMCF  
Dep. Environment: Crevasse-Splay  
Cum Oil: 0 MBBL

\[ q = 38 \text{ (1/5/1994)}, \quad d = 0.34, \quad b = 0; \quad K = 0.88 \text{ mD}, \quad DA = 109 \text{ Ac} \]
Depositional Environment PDCA

Production Decline Curve

Well: F.L. Blundell B-1  
Perf Zone: 3428-3433'  
Cum Gas: 598 MMCF

T.D. 5271'  
Dep. Environment: Barrier Island  
Cum Oil: 0 MBBL

q = 100 (5/27/1975), d = 0.09, b = 1; K = 6.99 mD, DA = 251 Ac
# Frio PDCA Character Summary

## Summary

<table>
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<tr>
<th>Depositional Environment</th>
<th>Average Porosity (%)</th>
<th>Gas</th>
<th>Oil</th>
<th>Cumulative</th>
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<td></td>
<td></td>
<td>$q_i$</td>
<td>$D_i$</td>
<td>$B$</td>
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<td></td>
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<tr>
<td>Barrier Island</td>
<td>25</td>
<td>100</td>
<td>0.09</td>
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</tbody>
</table>

Cumulative Oil

Cumulative Gas

Fluvial Channel

Barrier Island

Deltaic

Crevasse Splay
When expressed with a spatial context of 3D accommodation, depositional facies and their geometries record the discernable interplay between allocyclic and autocyclic processes.

For exploration, PDCA of sands within optimal parasequence sets provides further insight and potential predictive merit into determining how such reservoirs will behave under production.

For development, if augmented with 3D seismic and modeled with petroleum engineering hydrologic flow units, PDCA can potentially provide an incentive for the re-examination of mature fields for by-passed pay and new opportunities.

It is not just how thick, how porous, how permeable, what the conventional API cut-off is, or what one well shows, but instead what does the PDCA say about the sand facies reservoir characters: e.g. geometrically producible area, volume, time to payout, and recoverable reserves!
Sunrise or Sunset?

It's all in the mind...or, in the ground!
We are indebted to Quatro Oil & Gas, Inc. and especially to John Bradley for providing access to its extensive data for this study. We thank Corky Cummings for help with the PDCA and Schlumberger for furnishing its Petrel software to the Conoco Phillips School of Geology & Geophysics. JDP is especially appreciative for insight into differing perspectives of the autocyclic-allocyclic polemic provided in the classrooms of the University of Texas through the didactics of W.L. Fisher, L. Frank Brown, and A.J. Scott, later at Northwestern University with L. L. Sloss, and finally in the applied laboratory of Amoco International with Brian Barrick, Martin Cassidy, and O.W. Bud Hampton.