PS Modeling the Equilibrium of a Carbonate Tidal Channel: Preliminary Results*

Sanaz Borhani[1], Khaled Abdo[1], Christopher G. Kendall[2], Jasim Imran[1] and Enrica Viparelli[1]

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[1]Civil and Environmental Engineering, University of South Carolina, Columbia, South Carolina, United States
[2]Earth and Ocean Sciences, University of South Carolina, Columbia, South Carolina, United States (kendall@geol.sc.edu)

Abstract

The definition of the equilibrium profile of a tidal channel bounded seaward by the ocean and without a landward supply of water and sediment is a problem that has a long been the focus of study for clastic systems. The equilibrium of a clastic tidal channel is related to a constant relative base level and relatively coarse bed material, i.e., sand, defined as a condition in which the tidal channel does not experience net aggradation or degradation over a tidal cycle. In this study we compare the evolution of clastic and carbonate tidal channels with fine sand sediment size as bed materials; i.e., we neglect particles in the silt/mud range and the role of tidal flats. In the case of a carbonate system the problem is more complex than in the case of a clastic system since in situ "production of carbonate sediments" occurs in conjunction with geochemical processes that modify the carbonate particles and their properties. Further, the difference in density between the grains modifies the sediment transport processes of non-uniform material.

Our model for the long-term evolution of a carbonate tidal channel is based on assumptions and simplifications which involve modeling carbonate accumulation in terms of a specified carbonate "production rates" based on modern rates of carbonate accumulation. We further assume that:
1) There is no input of clastic sediments to the system,
2) Cementation processes are slow when compared to carbonate accumulation,
3) There is an absence of particles in the silt/mud range,
4) We treat the carbonate sediments as non-cohesive particles.
The one-dimensional de Saint Venant equations and the equation of conservation of bed material are solved numerically using an explicit finite difference scheme to study the case of a one-dimensional channel with constant width (dip section).

Here we present:
1) A comparison of bed profiles of clastic and carbonate tidal channels under constant base level conditions for different sediment densities - i.e., clastic vs carbonate - and different carbonate production rates - i.e., no carbonate production, uniform carbonate production and depth dependent carbonate production;
2) A comparison between experimental data and numerical simulations on bedload transport and deposition of a mixture of sediment of uniform grain size but differing in density.

Our preliminary results show that:
1) The in situ accumulation of carbonate sediments is responsible for the different bed profiles and hydrodynamic conditions of clastic and carbonate tidal channels;
2) Due to the in situ accumulation of carbonate sediments the morphodynamic equilibrium can probably be extended to carbonate systems in which physical accommodation is the dominant control;
3) The density difference between grains plays a significant role on sediment sorting patterns and should not be neglected in model simulations.

Selected References

Al-Husseini, M.I., 1997. Jurassic sequence stratigraphy of the western and southern Arabian Gulf: GeoArabia, v. 2/4, p. 361-382.

Boylan, A.L., D.A. Walthman, D.W.J. Bosence, B. Badenas, and M. Aureli, 2002, Digital rocks: lining forward modelling to carbonate facies: Basin Research, v. 14, p. 401-415.

Catuneanu, O., W.E. Galloway, C.G. St. C. Kendall, A.D. Miall, H.W. Posamentier, A. Strasser, and M.E. Tucker, 2011, Sequence stratigraphy: Methodology and nomenclature: Newsletters on Stratigraphy, Stuttgart, v. 44/3, p. 173-245.

Chaudhry, M.H., 2007, Open Channel Flow: Springer, 2nd Edition, 523p.

De Keyser, T.,and C.G. Kendall, 2014, Jurassic and Cretaceous sedimentary fill of intrashelf basins of the Eastern margin the Arabian Plate (abstract): Search and Discovery Article #90189 (2014). Website accessed June 30, 2017, http://www.searchanddiscovery.com/abstracts/html/2014/90189ace/abstracts/1838628.html.

De Keyser, T., and C.G. Kendall, 2014, Intrashelf basins respond to plate tectonic movement and paleogeographic position (abstract): Proceedings of SEPM Research Conference Autogenic Dynamics of Sedimentary Systems, August 3-6, 2014, Grand Junction, CO, USA, p 35.

Edgell, H.S., 1992, Basement tectonics of Saudi Arabia as related to oil field structures, *in* M.H. Rickard et al., editors, Basement Tectonics: Kluwer Academic Publishers, v. 9, p. 169-193.

Kendall, C. G., and A.S. Alsharhan, 2013, Reservoir character of carbonate/evaporite oil fields of the Middle East: A response to depositional setting and accommodation space (abstract): Search and Discovery Article #90163 (2013), http://www.searchanddiscovery.com/abstracts/html/2013/90163ace/abstracts/ken.htm.

Kendall, C.G., P. Moore, E. Viparelli, A.S. Alsharhan, T. De Keyser, and C. Kloot, 2014, Analysis of sequence stratigraphic models for the Jurassic-Cretaceous sedimentary fill of the intrashelf basins of the eastern margin the Arabian Plate (abstract): Search and Discovery Article #90189 (2014). Website accessed June 30, 2017, http://www.searchanddiscovery.com/abstracts/html/2014/90189ace/abstracts/1838628.html.

Kingston, D. R., C.P. Dishroon, and P.A. Williams 1983, Global basin classification system: AAPG Bulletin, v. 67, p. 2175-2193.

Lanzoni, S,. and G. Seminara, 2002, Long-term evolution and morphodynamic equilibrium of tidal channels: Journal of Geophysical Research, v. 107.C1, p. 1-1 – 1-13.

Neog, N., N.S. Rao, R. Al-Mayyas, T. De Keyser, C. Perrin, and C.G.St.C. Kendall, 2011, Evaporite Facies: A Key to the Mid Mesozoic Sedimentary Stratigraphy of North Kuwait: Search and Discovery Article #40682 (2011). Website accessed June 30, 2017, http://www.searchanddiscovery.com/documents/2011/40682neog/ndx_neog.pdf.

Parker, G., 2004, 1D Morphodynamics of Rivers and Turbidity Currents. Website accessed June 30, 2017, http://hydrolab.illinois.edu/people/parkerg/morphodynamics_e-book.htm.

Pomar, L., and C.G.St.C. Kendall, 2008, Architecture of carbonate platforms: A response to hydrodynamics and evolving ecology, *in* J. Lukasik and A. Simo, editors, Controls on Carbonate Platform and Reef Development: SEPM Special Publication no. 89, p. 187-216.

Rankey, E.C. and S.L. Reeder, 2011, Holocene oolitic marine sand complexes of the Bahamas: Journal of Sedimentary Research, v. 81, p. 9-117.

Viparelli, E., L. Solari, and K.M. Hill, 2015, Downstream lightening and upward heavying: experiments with sediments differing in density, Sedimentology, v. 62/5, p. 1384-1407.

Modeling the equilibrium of a carbonate tidal channel. Preliminary results

Sanaz Borhani, Khaled Abdo, Christopher G. St. C. Kendall, Jasim Imran and Enrica Viparelli
University of South Carolina at Columbia

ABSTRACT

The definition of the equilibrium profile of a tidal channel bounded seaward by the ocean and without a landward supply of water and sediment is a problem that has a long been the focus of study for clastic systems. The equilibrium of a clastic tidal channel is related to a constant relative base level and relatively coarse bed material, i.e., sand, defined as a condition in which the tidal channel does not experience net aggradation or degradation over a tidal cycle.
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THE PROBLEM

Several types of morphodynamic models have been developed and implemented to describe sediment transport, erosion and deposition in clastic fluvial, coastal and estuarine settings.

Governing equations for these models are the equations of conservation of mass and momentum to describe the characteristics of the flow, and one or more equations of sediment mass conservation to model suspended sediment transport, and sediment erosion and deposition.

Empirical relations are generally used to compute the sediment transport rates and/or the rates of suspended sediment entrainment and depositon.

Depending on the structure of the model more or less complex closure relations are needed to account for the interaction between the flow characteristics and the suspended sediment.

Some of these models describe the sediment as uniform; i.e., all the grains are assumed to have the same characteristic grain size; other models account for the non-uniformity of the sediment sizes; i.e., the sediment is described as a mixture of M uniform fractions with different characteristic grain diameters.

When sediment is modeled as a mixture of particles of different characteristic size, these models are able to reproduce some of the details of the size stratification in the longitudinal and vertical direction.

Can we use a similar modeling approach to describe carbonate systems?

Under conditions of constant flow and sediment load, asymptotic conditions of mobile bed equilibrium are defined for clastic systems.

At equilibrium, the flow and the sediment transport characteristics, as well as the average elevation of the bed surface, do not change in time.

Can we define analogous equilibrium conditions for carbonate systems, in which in situ "production" of carbonate sediments and geochemical processes are governing factors?

How would the equilibrium condition of a carbonate system, if exist, differs from the equilibrium of a similar clastic system?

Clastic sediments are generally modeled with the assumption that there is not a significant density difference between the grains.

This is certainly not the case for carbonate systems, in which the bulk grain density on average varies between 1.3 g/cm³ and 1.8 g/cm³ (L. Pomar personal comunication).

The diffrence in grain density becomes stronger in mixed clastic-carbonate systems, where the clastic grains have density of ~2.65 gr/cm³.

What is the effect of grain density on sedimentary processes?

How do grains differing in density affect sediment entrainment, transport and deposition?

Does density play a significant role on vertical and longitudinal particle segregation processes?

OUR APPROACH

We concentrate our attention on:

1) carbonate systems in which physical accommodation is the dominant control; and

2) the effects of density difference between grains on bedload transport, longitudinal and vertical sorting processes.

In particular we

1) developed a model for the of a tidal channel that explicitly accounts for carbonate "production", and we apply it to simulate tidal channel in the Bahamas; and

2) implemented and validate against laboratory experiments a model that is able to route sediment grains differing in density and to store density information of the deposit.

We neglect

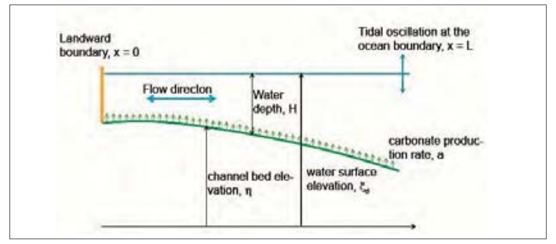
1) geochemical processes that modify carbonate particles and their properties;

2) interactions between grains differing in both size and density; and

3) changes in relative base level.

1D MORPHODYNAMIC MODEL FOR A CARBONATE TIDAL CHANNEL

Model Geometry,
we assume that the model tidal channel has constant width



Field case: a tidal channel in the Bahamas

Governing equations and numerical scheme

Hydrodynamic Phase:
The basic one-dimensional partial differential equations describing the unsteady water flow in a wide rectangular channel are the classical shallow water equations of mass and momentum, which read:

$$\frac{\partial H}{\partial t}+\frac{\partial UH}{\partial x}=0,\quad \frac{\partial HU}{\partial t}+\frac{\partial U^2H}{\partial x}=-gH\frac{\partial H}{\partial x}-gH\frac{\partial \eta}{\partial x}-C_fU^2$$

For hydrodynamic phase the system of Saint Venant equations is solved numerically in order to retain all the non-linear terms.

MacCormack Scheme (for interior nodes):
MacCormack scheme is an explicit, two-step predictor corrector scheme that is second-order accurate in space and time and is capable of capturing the shocks without isolating them. The method consists of two steps: prediction and correction. The former is made using a forward difference while the latter with backward finite difference.

Predictor: $\frac{\partial U}{\partial t}=\frac{U_i^*-U_i^k}{\Delta t},\quad \frac{\partial F}{\partial x}=\frac{F_i^k-F_{i-1}^k}{\Delta x}$

Substitution of these finite differences into Saint Venant equations and simplifications of the resulting equation yield: $U_i^*=U_i^k-\frac{\Delta t}{\Delta x}(F_i^k-F_{i-1}^k)-S_i^k\Delta t$

Corrector: $\frac{\partial U}{\partial t}=\frac{U_i^{**}-U_i^k}{\Delta t},\quad \frac{\partial F}{\partial x}=\frac{F_{i+1}^*-F_i^*}{\Delta x}$

Substituting these finite differences and $S=S_i^*$ into Saint Venant equation we obtain: $U_i^{**}=U_i^k-\frac{\Delta t}{\Delta x}(F_{i+1}^k-F_i^k)-S_i^*\Delta t$

In which the subscript ** refers to the values of the variables after the corrector step. The value of U_i at the unknown time level k+1 is given by: $U_i^{k+1}=\frac{U_i^{**}+U_i^*}{2}$

Morphodynamic Phase:
The Exner equation is a statement of conservation of sediment mass which is used to compute the temporal changes of bed elevation: $(1-\lambda p)\frac{\partial \eta}{\partial t}=\frac{\partial q_t}{\partial x}$

Numerical Approach:
We coupled the Exner and Saint Venant equations and solve them together using MacCormack scheme.
Adding Accumulation Rate: $(1-\lambda p)(\frac{\partial \eta}{\partial t}+a_0)=\frac{\partial q_t}{\partial x}$

a_0 is carbonate production rate and we defined t type of production rate, one is the maximum production rate on platform interior and the other is depth-dependent production rate which is defined according to the law:

$$a_0(H)=a_{\max 0}*\exp(\frac{-H}{Z_\lambda})(1-\exp(\frac{-H}{Z_w}))/\lambda_p$$

Where Z_λ characterizes the depth over which light drops off and; similarly, Z_w characterizes the depth over which fall-off in wave energy occurs.
the total (bedload and suspended) sediment load is computed with an Engelund and Hansen formulation as a function of the bed shear stress estimated from the flow hydrodynamic equations.

Boundary Conditions:
Upstream (Oceanward): The boundary condition at the estuary mouth is given by the sea level fluctuation. We assume that the water surface elevation at the channel mouth varies according to the law:
$Z=Z_0+A\cos(\omega t)$
Downstream(landward): At the landward boundary we assume the dead end condition. This situation corresponds to the assumption of vanishing discharge at the landward end of the computational domain. We used negative characteristic equation to get the U and H at land side.

Model parameters

t	Temporal coordinate
x	longitudinal (dip) coordinate
g	acceleration of gravity
C_f	non-dimensional friction coefficient
λ_p	bed porosity
q_t	volumetric bed material load per unit width
U	depth-averaged flow velocity
dt	temporal increments used for the numerical solution of the equations
dx	spatial increments used for the numerical solution of the equations

Initial inputs

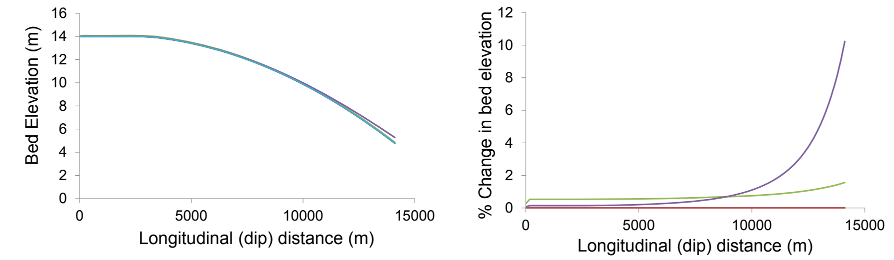
$B(m)$	1
$L(m)$	14000
C_f	0.003
λ_p	0.4
$Z_0(m)$	14
$A(m)$	0.75
$D(m)$	0.0003
R	1.65, 1.5
$a_{0max}(m/ky)$	0.02

Model results

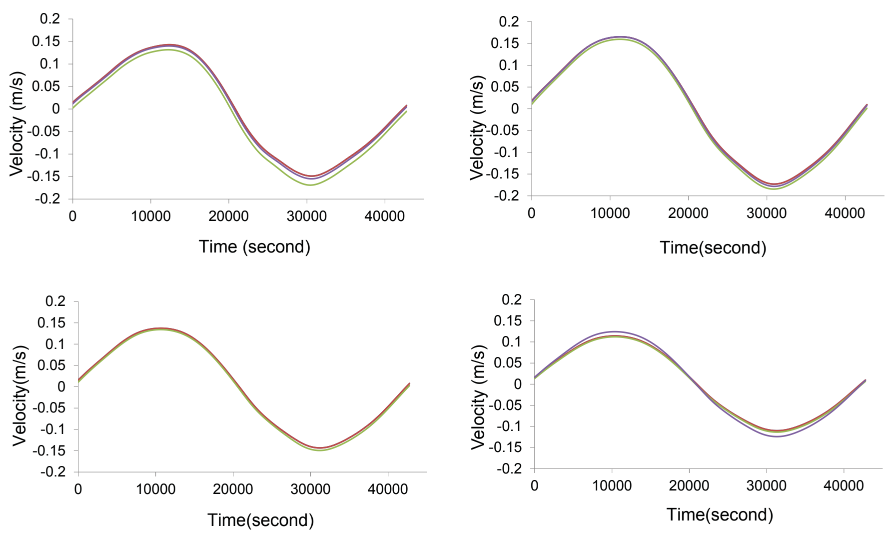
We performed three 1000 year-long simulations characterized by the same initial condition and tidal forcing. Run 1 – red line in the plots – is our base case and refers to a clastic system, sediment density = 2.65 g/cm3 and zero in situ sediment production rate. Run 2 – green line in the plots – pertains to the case of a carbonate system without in situ sediment production rate, i.e. sediment density = 1.5 g/cm3. Finally, Run 3 – purple line in the plots – describes a carbonate system with depth-dependent in situ sediment production rate.

The initial longitudinal profile is represented with the grey line in the elevation plots.

Channel bed elevation - longitudinal profiles



Flow velocities



AND SO WHAT?

1) One-dimensional morphodynamic models are able to account for production of carbonate grains. Depending on the complexity of the model the production rate can be a function of modeled physical parameters, such as water depth.

2) The density difference between sand/silt grains, as well as the difference in grain size, plays a significant role in longitudinal – i.e., dip - sorting patters. One-dimensional morphodynamic models are able to capture longitudinal sorting patterns in systems of particles differing in both size and density. Thus, these models are potentially able to reproduce longitudinal sorting patterns in mixed clastic-carbonate systems.

3) The implementation of a one-dimensional morphodynamic model that is able to reproduce the spatial variation of density and size in the dip direction is relatively straightforward. However, basic research is needed to determine relations to estimate bedload transport, sediment entrainment in suspension and sorting processes associated with gravitational effects – e.g., avalanches on the lee side of bedforms - in the case of a mixture of sediment grains differing both in size and density.

4) Morphodynamic models coupled with larger scale sequence stratigraphy models, well logs and seismic images have the potential to be used in the exploration of hydrocarbon reservoirs and explore the connectivity between different potential reservoir bodies.

FUTURE PLANS

1) Implement the proposed modeling approach in an in-house built, existing and more robust computational framework, i.e., finite volume and not finite difference, which is able to reproduce two-dimensional – i.e. dip and strike - flow hydrodynamics on complex geometries.

2) Perform basic research on the interaction between grains of different size and density to characterize bedload transport, sediment entrainment and sorting processes for mixtures of grains with different densities and sizes.

3) Perform experimental numerical experiments to validate the proposed modeling framework at field scale in modern – e.g. Bahamas, poster 3 – and ancient – e.g., Middle East, poster 2 – settings.

ACKNOWLEDGMENTS

We sincerely thank Stefano Lanzoni and Luca Solari for the help and the discussions on modeling clastic tidal channels.

COMPARISON BETWEEN LABORATORY EXPERIMENTS AND NUMERICAL SIMULATIONS OF BEDLOAD TRANSPORT AND DEPOSITION OF MIX-DENSITY SEDIMENTS

Experiments: uniform grain size but different densities

The runs started with an empty flume. A laboratory delta formed and migrated downstream.

Non-equilibrium measurements of water surface elevation, bed elevation and density of the bed surface were taken when the deposit was 3 m, 5 m, 7 m long. Elevations were measured with a point gauge; surface samples were collected using a syphon.

When the flow and the sediment transport reached conditions of mobile bed equilibrium, the bed and water surface elevations, the density of the bed surface and the density of the deposit were measured again.

During the experiments small scale bedforms formed on the delta top.

The sediment mixtures D = 0.5 mm

Mixture A, R = 1.43,
43% plastic, 19% sand, black diamond, and garnet

Mixture B, R = 2.33
50% sand and garnet

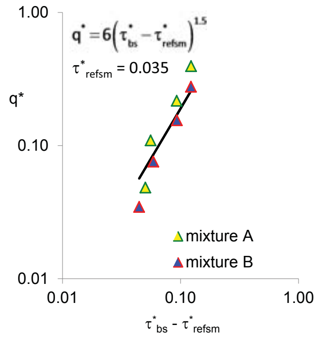
R = submerged specific gravity
D = grain size

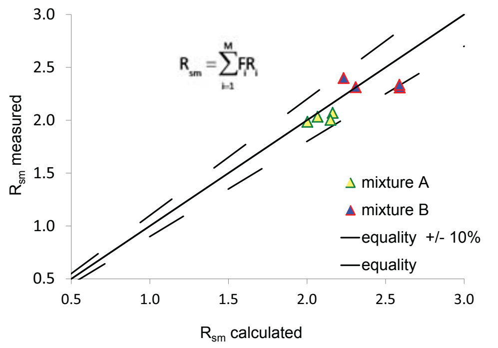
The experimental conditions

Run	flow rate (l/s)	feed rate (g/min)
1A	4	45
2A	4	100
3A	4	200
4A	4	300
1B	6	60
2B	6	135
3B	6	270
4B	6	490

Main Observations

The measurements of the density of the bed surface and of the deposit show:
1) preferential deposition of heavy material in the upstream part of the aggrading deposit, which result in a pattern of downstream lightening;
2) preferential deposition of light material – plastic for mixture A and sand for mixture B – in the lowermost part of the bedform lee faces and of the delta front, which resulted in a pattern of upward heavying. Bedforms were significantly higher in the mixture B experiments.





Density specific surface based bedload relation

<u>Notation and definitions</u>

$q^*=\frac{Q_b}{B\sqrt{R_{sm}gD}D}$ non-dimensional total volumetric bedload transport rate per unit channel width

R_{sm} = submerged specific gravity of the bed surface averaged over the M density classes; g = acceleration of gravity, B = channel width, Q_b = volumetric bedload transport rate

$\tau^*_{bs}-\tau^*_{refsm}$ excess non-dimensional bed shear stress - Shields number

τ^*_{refsm} = reference Shields number for significant bedload transport

$\tau^*_{bs}=\frac{\tau_{bs}}{\rho R_{sm}gD}$ non-dimensional bed shear stress – Shields number

ρ = density of the water

$q_i^*=\frac{Q_{bi}}{F_iB\sqrt{R_igD}D}$ non-dimensional density-specific volumetric bedload transport rate per unit channel width

R_i = generic submerged specific gravity; F_i = volume fraction content of particles with density R_i in the bed surface

$q_i^*=6(\tau^*_{bsi}-\tau^*_{refsmi})^{1.5}$ our density-specific bedload relation

$\tau^*_{bsi}=\frac{\tau_{bs}}{\rho R_igD}$ density-specific Shields number

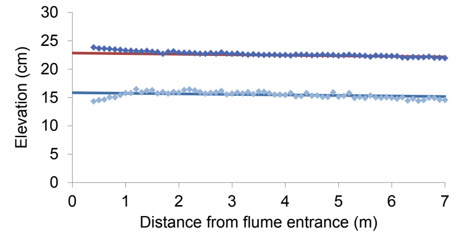
$\tau^*_{refsmi}=\left(\frac{R_i}{R_{sm}}\right)^{-2}\tau^*_{refsm}$ unnamed analog of the hiding/exposure function

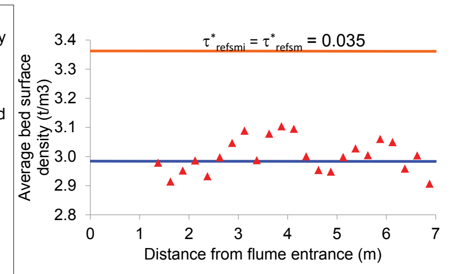
In a mixture of unisize particles differing in density, the light grains become harder to move than in the case of uniform light material

Active layer model simulations: comparison between numerical and experimental results

To model the laboratory experiments, we implemented an active layer model of delta growth that is able to account for the different density of the sediment grains. The comparison between numerical and experimental results for runs 2A and 2B is presented. Simulations were performed using our density specific bedload relation (blue lines in the density plots). Simulations were then repeated under the assumption that the interaction between unisize grains differing in density is negligible (orange lines in the density plots), i.e. τ^*_{refsmi} = τ^*_{refsm} = 0.035, due to the absence of hiding/exposure effects – all the grains have the same grain size (more or less).

Comparison numerical – lines – and experiments – dots – at the end of Run 2A (relatively small amplitude bedforms)





Governing equations

1) the backwater equation to compute the flow properties;
2) the equation of total – i.e., summed over all the densities - sediment mass conservation to compute the deposit elevation;
3) the density specific equation of conservation of sediment in the active layer to compute the density distribution of the active layer;
4) integral shock condition to compute delta progradation rates before the deposit reaches the sediment trap;

Preliminary results

An active layer model is able to reasonably reproduce the average density of the bed surface in systems carrying a mixture of unisize particles differing in density, if
a) the change in grain mobility associated to the interaction between grains with different density is accounted for, and
b) small scale bedforms are not too large.

The model underestimates the streamwise decrease in bed surface density during channel bed aggradation. We suspect that this is associated to the vertical sorting on the bedform lee sides.

REFERENCES

Al-Husseini, M.I. 1997. Jurassic sequence stratigraphy of the western and southern Arabian Gulf. GeoArabia, v. 2, no. 4, p. 361-382.
Boylan, A.L., Walthman, D. A., Bosence, D. W. J., Badenas, B. and Aureli, M., 2002, Digital rocks: lining forward modelling to carbonate facies, Basin Research 14, 401-415.
Catuneanu, Octavian, William E. Galloway, Christopher G. St. C. Kendall, Andrew D. Miall, Henry W. Posamentier, André Strasser, and Maurice E. Tucker, 2011, "Sequence Stratigraphy: Methodology and Nomenclature", Newsletters on Stratigraphy, Stuttgart, Vol. 44/3, 173–245
De Keyser, Tom; Kendall, Christopher G., 2014, Jurassic and Cretaceous sedimentary fill of intrashelf basins of the Eastern margin of the Arabian Plate, 2014 AAPG Annual Convention and Exhibition, 6-9 April, 2014, at George R. BrownConvention Center, Houston, Tx.
De Keyser, Thomas; and Kendall, Christopher; 2014, Intrashelf basins respond to plate tectonic movement and paleogeographic position, Proceedings of SEPM Research Conference Autogenic Dynamics of Sedimentary Systems, August 3-6, 2014, Grand Junction, CO, USA ; Abstract, p 35.
Edgell, H.S. (1992). Basement tectonics of Saudi Arabia as related to oil field structures, In: Basement tectonics 9, M.H. Rickard, & al., (Eds), pp. 169-193, Kluwer Academic Publishers, Dordrecht
Kendall, Christopher G.; Moore, Phil; Viparelli, Enrica; Alsharhan, Abdulrahman S., De Keyser, Tom; and Kloot, Cameron, 2014, Simulation and analysis of sequence stratigraphic models for the Jurassic Cretaceous sedimentary fill of the Eastern margin the Arabian Plate; 2014 AAPG Annual Convention and Exhibition, 6-9 April, 2014, George R. Brown Convention Center, Houston, Tx.
Kendall, Christopher G.; Abdulrahman S. Alsharhan, 2013, Middle East: A Response to Depositional Setting and Accommodation Space, 2013 AAPG Annual Convention and Exhibition, 19 - 22 May 2013 in Pittsburgh, Pa
Kingston, D. R., Dishroon, C. P., and Williams 1983, Global basin classification system. AAPG Bull, 67: 2175-2193
Lanzoni, S. and Seminara, G., 2002, Long-term evolution and morphodynamic equilibrium of tidal channels, Journal of Geophysical Research 107 C1, 3001, doi: 10.1029/2000JC000468.
M. Hanif. Chaudhry, Open Channel Flow, Springer, 2nd Edition, 2007
Neog, Nilotpaul., Narahari S. Rao, Rawan Al-Mayyas, Thomas De Keyser, C. Perrin, and C. G. St.C. Kendall: 2010, Evaporite Facies: A Key to the Mid Mesozoic Sedimentary Stratigraphy of North Kuwait; Mixed Carbonate/Evaporite Successions (SEPM) Program of the AAPG 2010 International Conference & Exhibition (ICE) Calgary.
Parker, G., 2004, 1D Morphodynamics of Rivers and Turbidity Currents. Available at: http:// hydrolab. illinois.edu/people/ parkerg/?q=people/parkerg/
Pomar, L. and Kendall, C. G. St. C., 2008, Architecture of carbonate platforms: A response to hydrodynamics and evolving ecology. In: Controls on Carbonate Platform and Reef Development – J. Lukasik & A. Simo (Eds.). ISBN 978-1-56576-130-8, SEPM Special Publication No. 89, p. 187-216
Rankey, E. C. and Reeder, S. L., 2011, Holocene oolitic marine sand complexes of the Bahamas, Journal of Sedimentary Research 81, 9-117.
Viparelli, E., Solari, L. and Hill, K. M., 2015, Downstream lightening and upward heavying: Experiments with sediments differing in density, Sedimentology, doi: 10.1111/sed.12187

INTRODUCTION TO ANALOGUES

"Grain" carbonates are often a major component of the Giant Oil Fields of Middle East, North America and beyond. These grain carbonate reservoirs are associated with high energy shoals updip from carbonate bank margins. The objectives of our experiments is that these be used by exploration and production geologists who often need to predict the width, thickness and character of these grain carbonate shoals deposit preserved in the subsurface and an explanation of their occurrence as both a function of the accommodation and the energy of the waves and tidal exchange.

A further intent of this study is to match the results of experiments reported here to examples from modern settings as well as outcrops and cores from oil fields. Analogues include grain carbonate shoal deposits of the Holocene of the Bahamas, outcrops that include those of Spain and Italy, and subsurface analogues (the Jurassic Marrat of Kuwait and the Hanifa Formation and the Arab-D (e.g., Qatif Field) in Saudi Arabia, the Smackover Formation in northern Louisiana and south Arkansas, the Aptian Shuaiba Formation (e.g., Bu Hasa Field) and the Cenomanian Mishrif Formation (e.g., Umm Addalh Field) of the Arabian Gulf.) The intent is that the experiments of this study will reduce the risk in predicting the size of grain carbonate shoals ahead of the drill in the subsurface.
We plan to use the relationship between flow regime and grain size distribution and the ripples and cross beds they produce for particular flow regimes and grain size. Our mantra is "better understanding" of the physical processes in carbonate settings derived from our studies will lead to "better predictions" of potential reservoir net/gross ratios of the intrashelf basins of the Eastern margin of the intrashelf basins of the Eastern margin thickness. Our hope is that geologists use our results to predict layer thickness and areal distribution?

As indicated grain carbonate reservoirs are common to many of the Giant fields of the Middle East, be they in Iran, Saudi Arabia, Kuwait, Qatar, the UAE or Oman. Critical conceptual sequence stratigraphic models for exploration and production can be analyzed with sedimentary computer simulations of sedimentary fill of the intrashelf basins of the Eastern margin of the Arabian Plate.

To date examples from the Jurassic and Cretaceous sedimentary fill of the Eastern margin have been simulated on a megascale to potentially set the scene for the results of the small scale simulations reported in this study. Parts of the geologic section and regions of the Middle East included are:

1) Evolution of the Toarcian fill of the Marrat Basin from Lower Jurassic evaporites through a prograding carbonate margin with basinal argillaceous carbonate capped by evaporites;

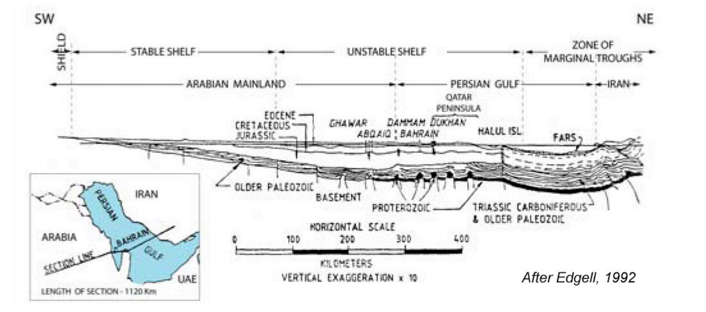
2) Evolution of the Middle to Upper Jurassic fill of the Hanifa Basin from argillaceous carbonates to evaporites capped by Cretaceous carbonates, and

3) Aptian/Albian fill of the Bab Basin during a glacially induced sea level low. Results for the Marrat and Hanifa Basins simulations demonstrate the Lower to Middle Jurassic onlapped the uplifted Arabian plate margin in Kuwait, Saudi Arabia, the UAE and Oman in two phases of carbonate margin progradation and basinward infilling. The Middle Jurassic ended with uplift and subaerial exposure and progressive erosion of the Tuwaiq and Dhruma Formations along the plate margin. The margin then collapsed with a drowning unconformity. Away from the platform margin of the intra-shelf basin accumulation.

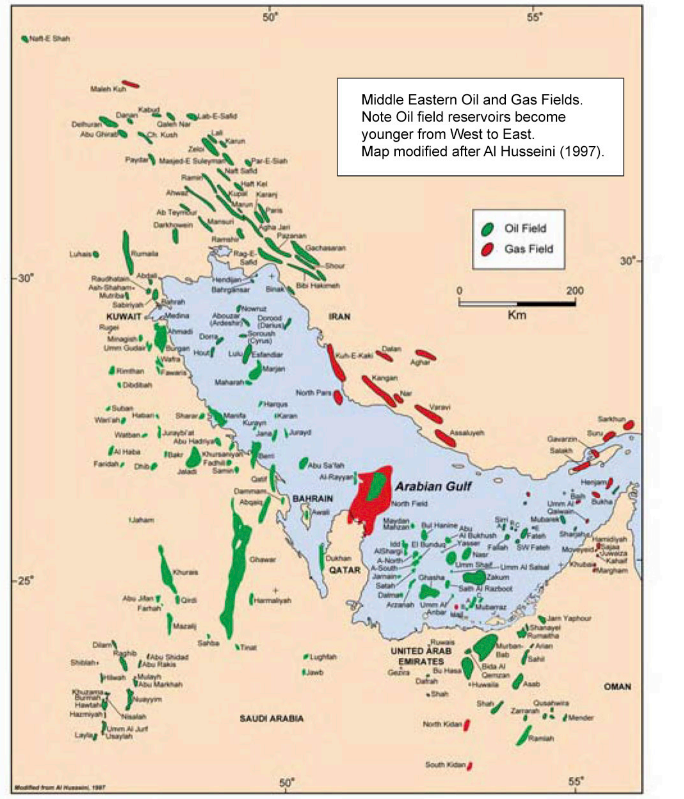
In Early Cretaceous times the platform of the Arabian Shield extended to North Oman with deposition of argillaceous hemipelagic carbonates of the Habshan. The lack of evaporites supports a climatic change from the arid climate of the Jurassic to a humid climate of the Cretaceous.

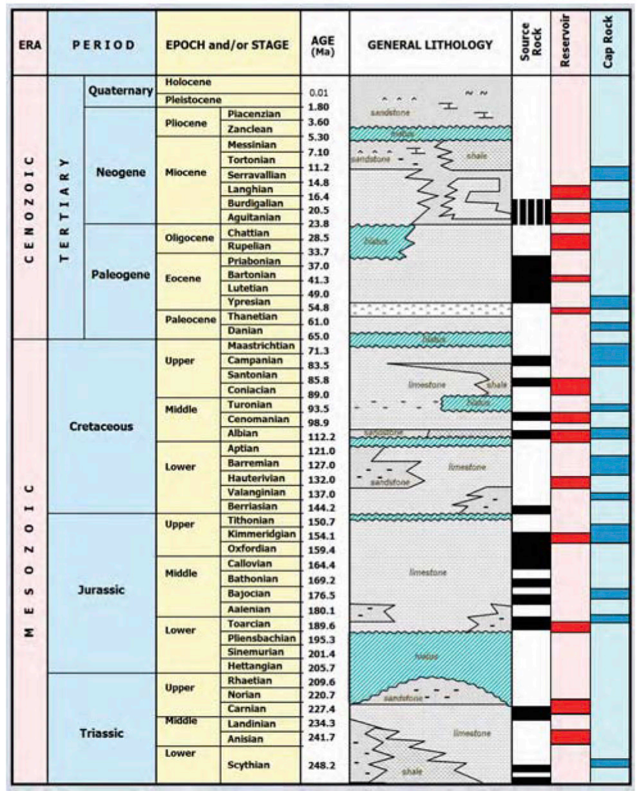
The simulation of Mid Cretaceous carbonates supports their division into the second order supersequences of Early Aptian and Late Aptian carbonate platforms aggrading and prograding while filling the Bab intrashelf basin. An unconformity initiates the sequence with westward prograding lowstand clinoforms also onlapping onto the southwestern margin of the Bab intrashelf basin and its Early to early Late Aptian carbonate platform. The simulation captures the initial sharp sea-level drop of 35–40 m from the early Upper Aptian shelf break to the toeset of the first lowstand clinoform, and the sea-level drop by another 10 m during the progradation of the following eight clinoforms. Each pulse of progradation of the clinoforms is modeled over 405 ky. Cross-sections illustrate the initial sharp sea-level drop of some 40 m followed by continued slow sea-level fall producing lowstand clinoforms prograding towards the basin.

Output geometries display a sequence stratigraphic framework of erosional and depositional surfaces of the simulated section enabling the extension of interpretation of depositional setting and predictions of lithofacies geometries away from well data. This aids prediction of facies likely to contain both hydrocarbon and water resources and their characteristic fabrics, identifying and constraining key factors that control sequence stratigraphic geometries and architectures, including rates of sedimentation, eustatic sea level changes.



Geological Cross Section of the Arabian Gulf Basin of sedimentary section overlying the halokinetic Proterozoic Hormuz Series. The younger Paleozoic to Mesozoic to Tertiary sediments sequester oil and gas fields whose reservoirs become younger from west to east.



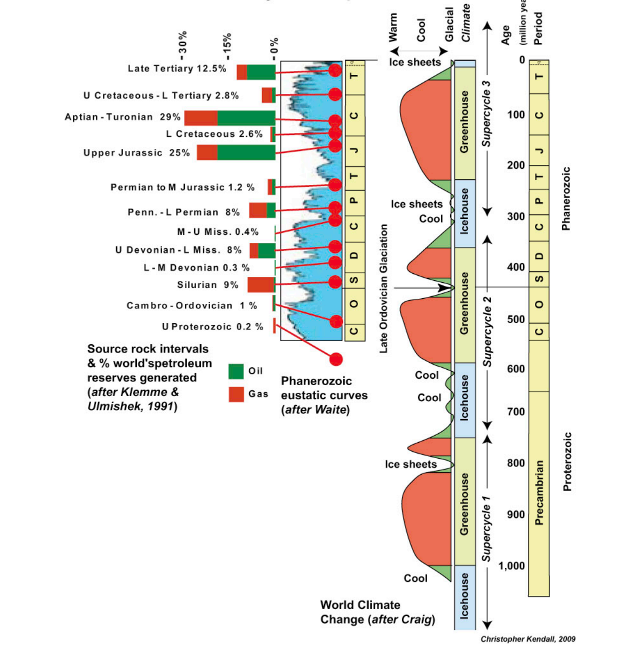


Middle East Source Rocks, Reservoir and Seals (After Kendall and Alsharhan 2013)

Plate Tectonic Evolution of Southern Tethys

The region outlined by the red oval traces the evolution of the Southern Tethys basin seaway that has existed since the Precambrian This body of water flanked what is now the Arabian Plate and includes the protoTethys, paleoTethys, and neoTethys Oceans. The evolving geographic location of this ocean and the geology that underlies it is responsible for the accumulation of thick stratigraphic packages. These extend across the Arabian Plate through the Zagros and Taurus Mountains, Levant-Cyprus and North Africa. Sediments accumulated both in the Tethyan basin and on the adjacent Precambrian metamorphic and igneous basement rock of Pangea, Gondwanaland, and Southern Eurasia. The shared geologic history of the Southern Tethys region means similar tectonic and depositional settings and a stratigraphy that can be correlated across the region from the Precambrian through Cenozoic. These stratigraphic packages contain many source, seal, and reservoir rocks that make up both the proven and underexplored petroleum systems of the region.

Cyclic Changes in Climate, Sea Level, Organic Productivity & Sequestration

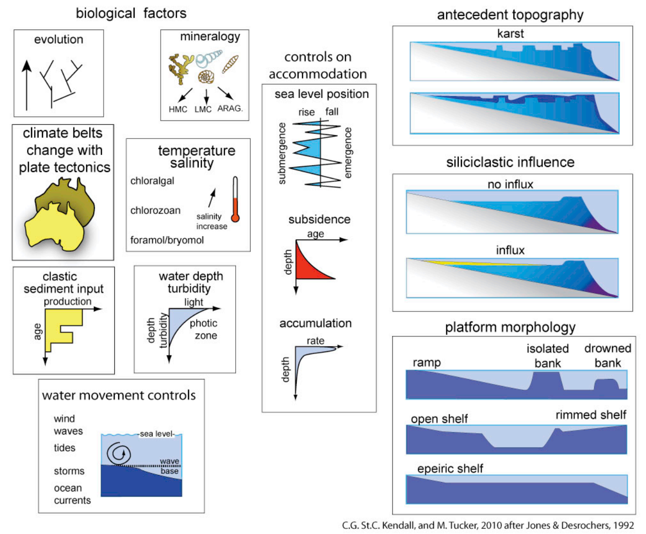


While Gondwanaland evolved through extension, compression, and basin restriction this also had impact on source rocks. Concurrently climate of the Arabian plate was affected by latitude rain shadow and,as illustrated above,green house and ice house climatic events and effects of transgressions and super-plumes that helped nutrients to flourish. The diagram tracks the resultant significant source rocks through time on the Arabian plate and this explains why the intrashelf basins or ISBs were so rich in organic material sequestered during rapid marine transgressions.

Organic Matter and Plate Tectonic Evolution of Arabian Gulf

In the diagrams above and the maps of the evolving continents below the red oval traces that region that was an organic sweet spot through Geologic History. There appear to be strong ties between plate setting and climate that can be used to understand the occurence of organic matter and evaporites and rain shadow and their proximity to the continental margins and narrow marine bodies match those seen of the break-up and then collisions associated with the history of Gondawanaland. Arid climates and organic matter in the marine settings in the zones associated with rain shadow appear common to the Middle East and the southern margin of the Tethys Ocean.

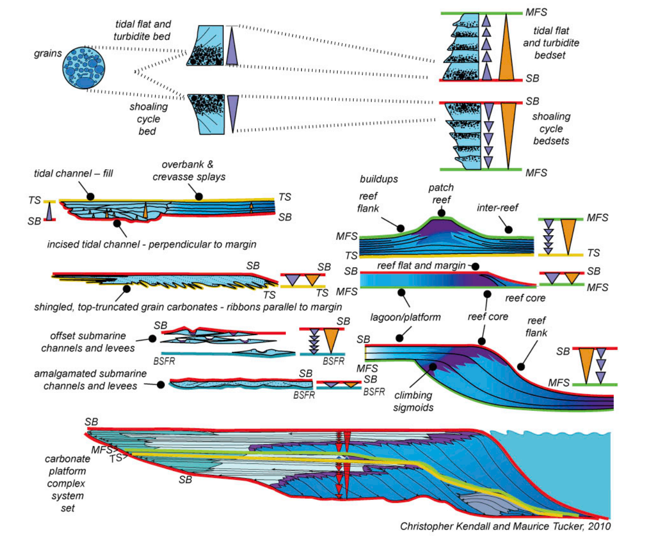
Controls on Carbonate Accumulation



C.G. St.C. Kendall, and M. Tucker, 2010 after Jones & Desrochers, 1992

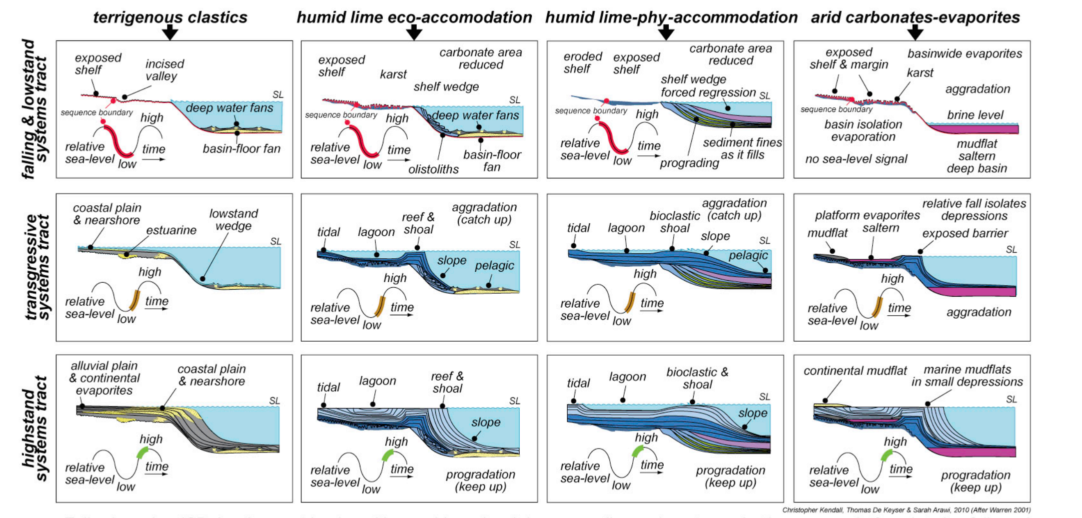
This phase diagram ties carbonate production to the controls by Gondwanaland's tectonic evolution through extension, compression, and basin restriction and the arid tropical climate of the Arabian plate. It shows how biologic factors, water movement and pre-existing topography, also controls within the intrashelf basins (ISBs), affected carbonate production and accumulation.

Hierarchal Arrangement of Carbonate Geometries & Sequence Surfaces



Christopher Kendall and Maurice Tucker, 2010

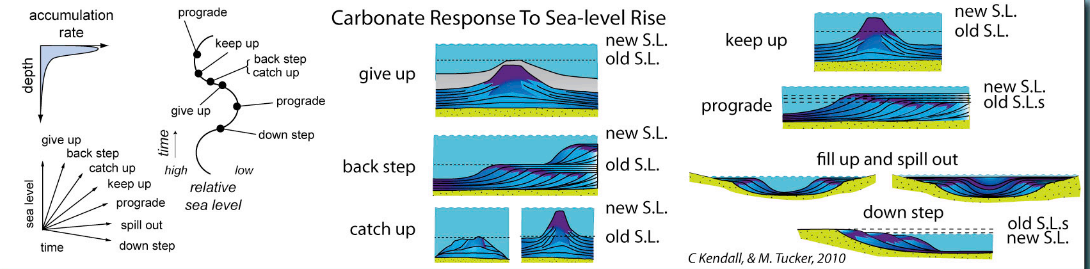
Styles of Sedimentary Fill of Intrashelf Basins



Christopher Kendall, Thomas De Keyser & Sarah Arawi, 2010 (After Warren 2001)

Following a low ISB development begins with a rapid sea level rise, exceeding carbonate production across platform interior, followed by aggradation on margin with a starved basin center. ISB margin then progrades and infills the basin, commonly less than 100 m deep.

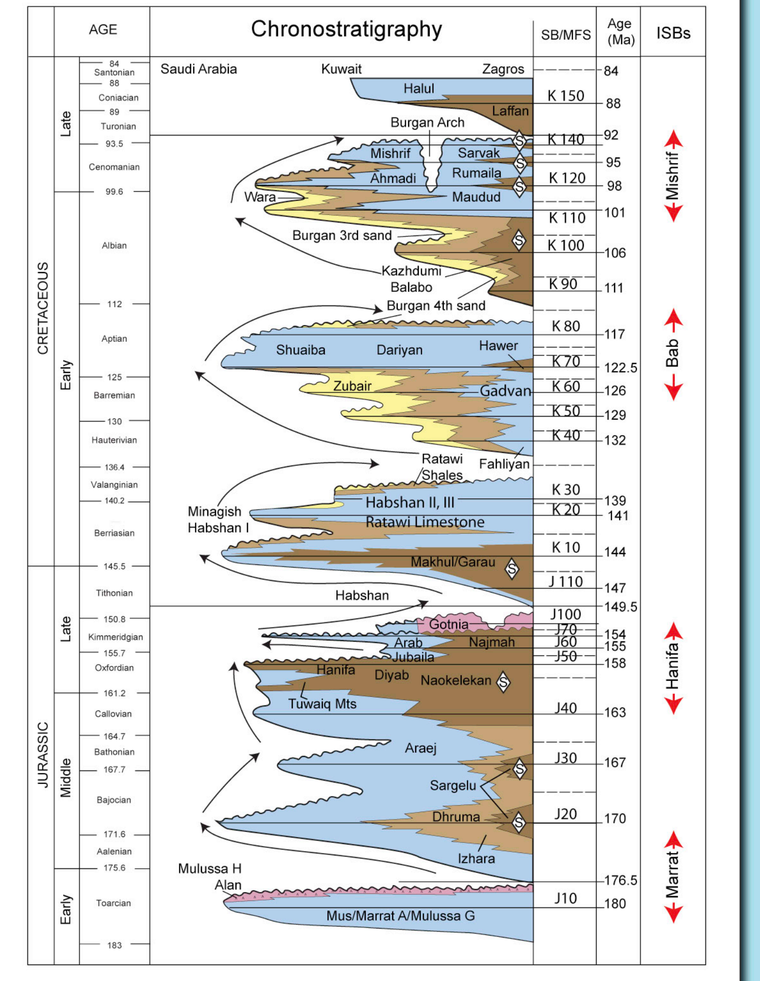
Carbonate Response To Sea-level Rise



C Kendall, & M. Tucker, 2010

In diagrams to upper left and upper right carbonate geometries change their character in response to changes in accommodation and tend to quickly fill any space generated by changes in base level (either a response to changes in eustasy or in tectonic subsidence). Sedimentary simulations varying accommodation and rates of sediment accumulation form carbonate stacking patterns and prograding geometries that keep up, catch up and give up with respect to sea level position.

Chronostratigraphy



Marrat, Hanifa, and Bab Intrashelf Basins

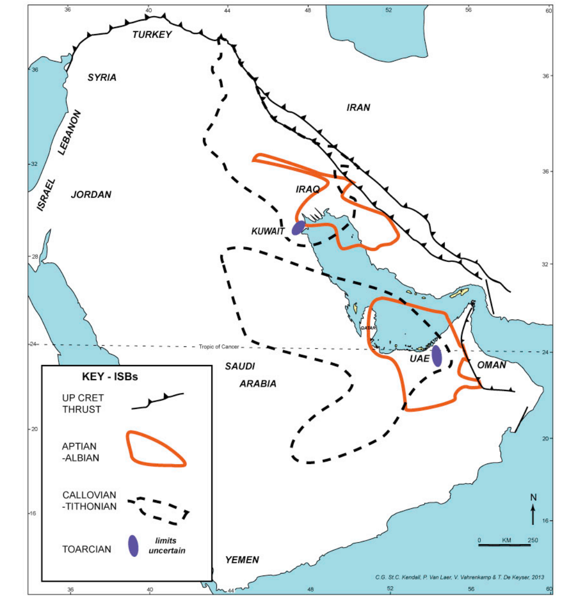
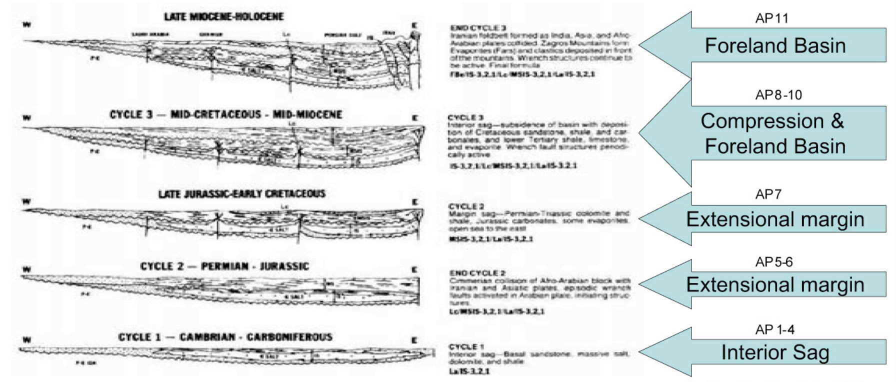
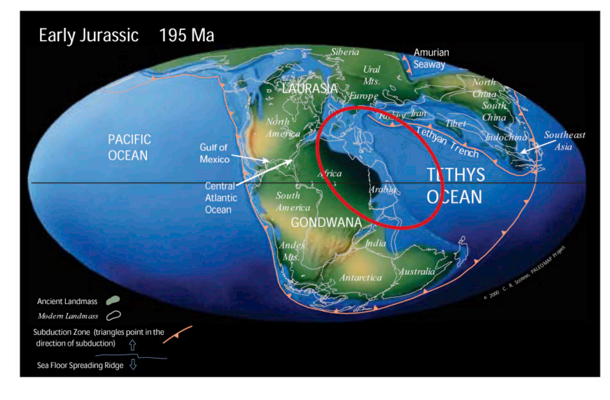


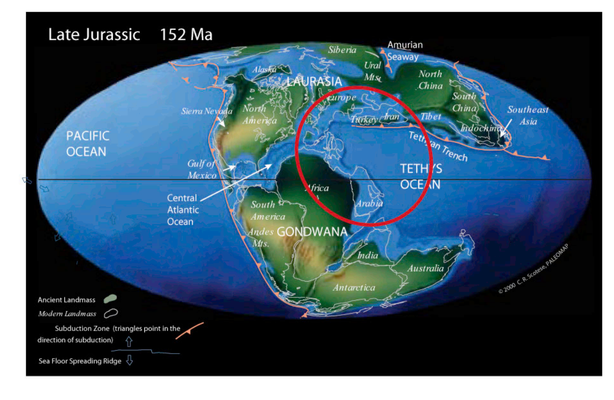
Plate Tectonic Evolution of Arabian Gulf

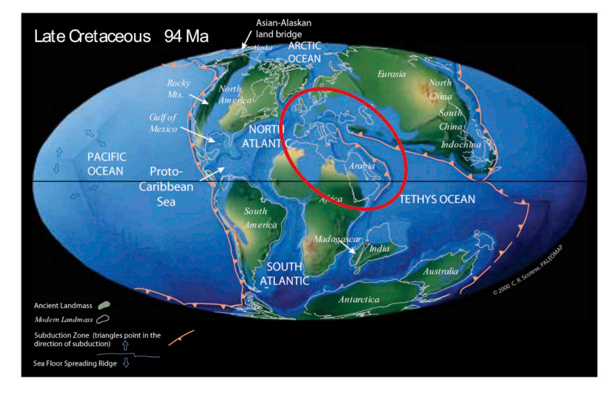


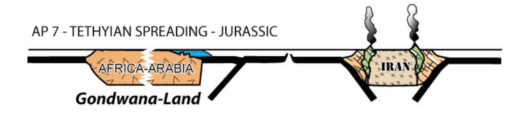
After Kingston et al, 1983

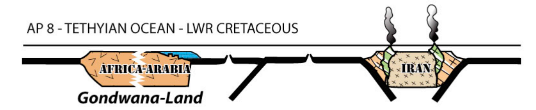
The stratigraphic framework of the Arabian Plate (AP) margin is subdivided by eleven major unconformity surfaces bounding tectono-stratigraphic mega-sequences (AP 1-11 of Sharland et al., 2001). These were created during low-frequency tectonic events associated with cycles of tectonic plate motion (Wilson, 1966). It is further subdivided sixty-three higher frequency events related to eustatic changes in sea level and varying rates of sediment accumulation (Sharland et al, 2001). These events are tied to periods of maximum flooding (MFS) associated with maximum regional transgressions, non-deposition and/or unconformities, and sediment accumulation. Together these tectonically and eustatically produced surfaces provide chronostratigraphic order to the sedimentary fill tied to radiometric and biologic markers (Sharland et al., 2001).











The Mesozoic sedimentary sections overlying the Arabian Plate are a mix of carbonate, evaporites organic-rich carbonates that collected behind barriers formed by the movement of what was an original Hercynian horst and block terrain adjacent to the southern shore of the Tethys Ocean. These barriers accumulated sediment over them and limited access to the sea. This led to the punctuation of the geological record with evaporites, carbonates and source rocks associated with an adjacent arid climate. These bodies of the seawater occurred as isolated linear belts of interior drainage with restricted entrance to the open Tethys Ocean. Regional drainage probably tended to flow into this basin, and the air system was that of the arid tropics. There was a wide envelope formed by the surrounding subcontinents of Arabia and Africa.

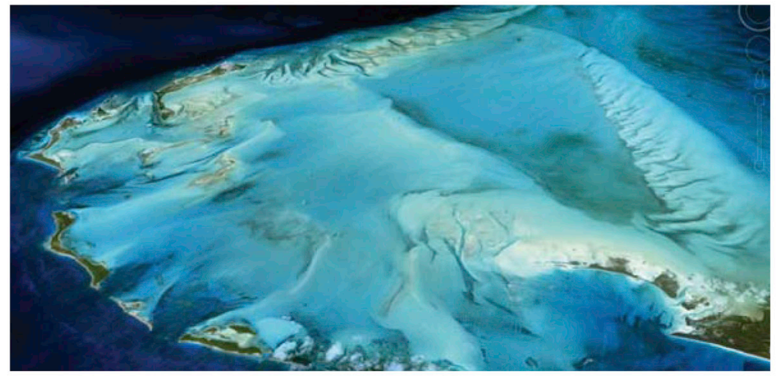
Chronostratigraphic Chart for Arabian Plate ISBs

As indicated in the chronostratigraphic chart to upper right, Jurassic Arabian Plate ISBs include the Marrat, Hanifa, Najmah, and Gotnia basins often filled by shallow marine arid-climate limestones and dolomites with common evaporites and interbedded minor transitional marine shales and basin margin grain carbonates. Cretaceous ISBs include: Garau of Iraq, Kazhdumi of Iran and Bab of the UAE, and the Mishrif and Najaf ISBs of the UAE and Iraq, respectively. Fill is dominantly humotropic carbonates with dolomites and shales.

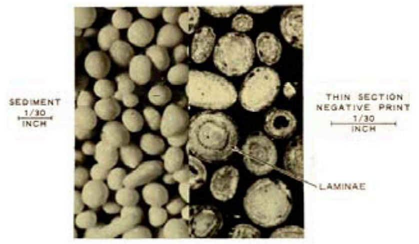
Modern Carbonate Bank Grain Carbonates

Louis Pomar among many (Pomar 2001a; Pomar 2001b; Pomar et al 2005; Pomar and Hallock 2008; Pomar, and Kendall 2008; Pomar and Tropeano 2001) has suggested that large-scale cross-bedded carbonate grainstones of bank margins that accumulate in shallow tropical water settings and form common hydrocarbon reservoirs. There are numerous depositional models in the geologic literature that explain carbonate reservoir characteristics and their origin. Variation in this character, particularly the composition of their allochems, depends on climate and tectonic setting both for the sediment source and particularly the processes controlling grain accumulation. Common models for marine carbonate cross-bedded geometries are the sand shoals and beaches, tidal bar belts, marine sand belts, platform interior sand blankets, flood- and ebb-tidal deltas, etc. of the Bahamas (Ball, 1967; Halley et al., 1983, Harris, 2009). Bank-margin carbonate sands occur repeatedly throughout the geologic record, as for instance, the Bahamas illustrated here. There are other potential settings that can also be used to interpret other accumulating carbonates in the geologic record.

Cat Cay Sand Shoals - Tides and Wave



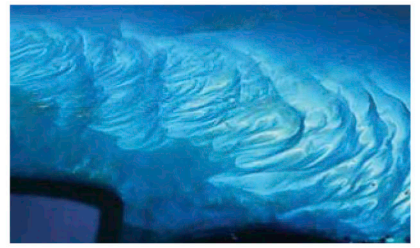
Chub Cay Sand Shoals - Mix of Tidal and Wave Processes



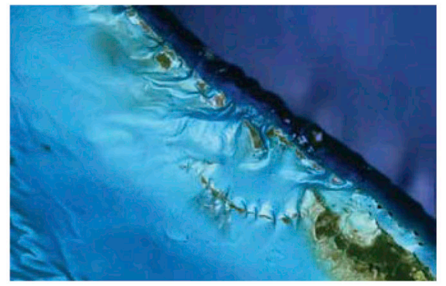
Cat Cay Sand Shoal Ooid Fabrics

Cat Cay Sand Shoals Cross Bedded Ooids

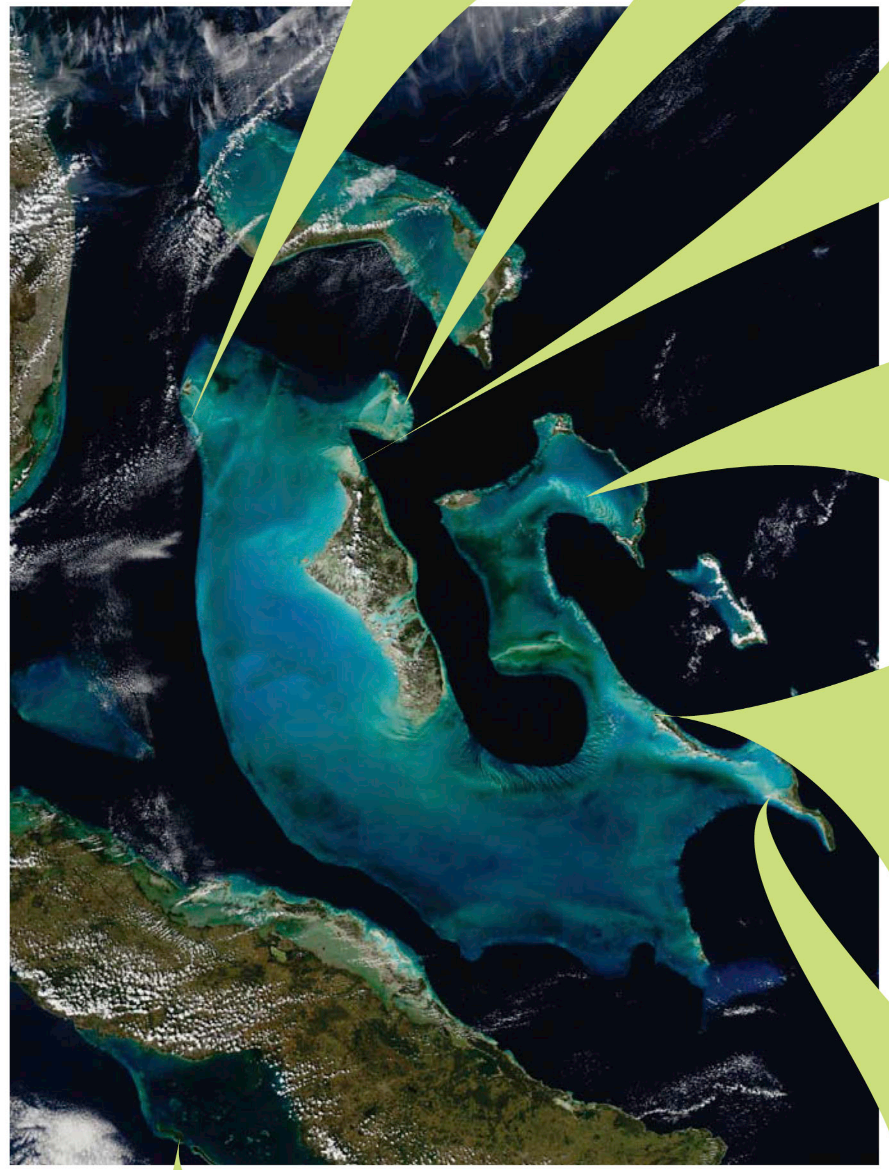
Joulters Cays - Tidal Channels and Barrier Islands



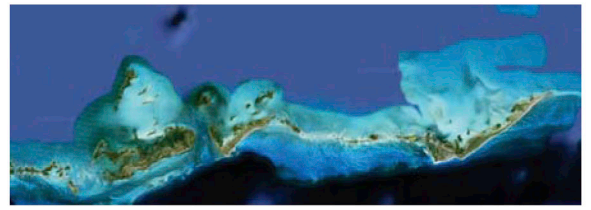
Exumas Banks Ooid Shoals-Tidal Channeling Reworked by Waves



Tidal and Waves Modulate Sand Shoals in Vicinity of Lee Stocking Island

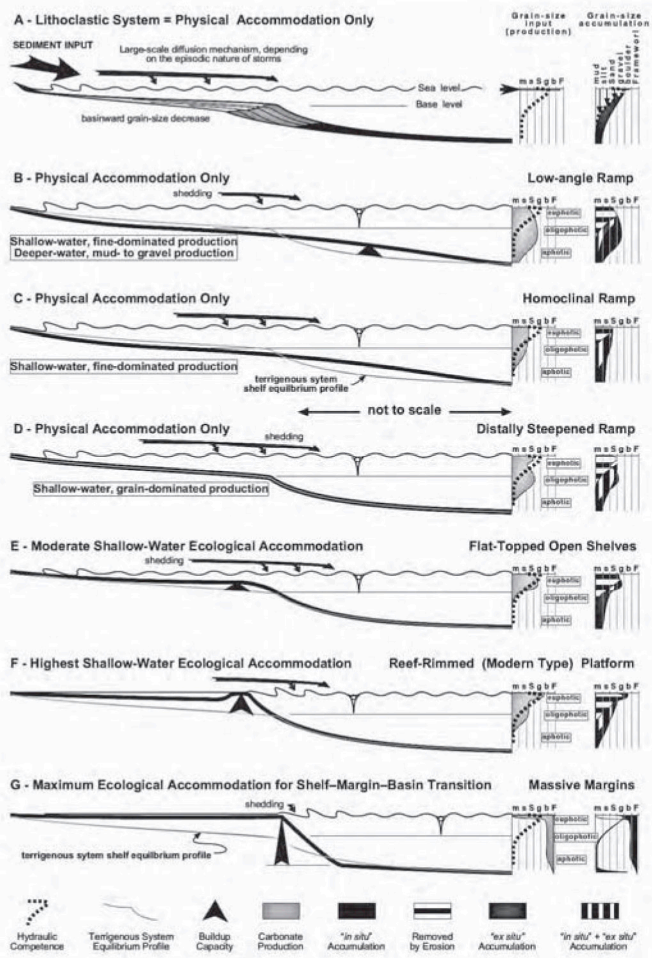


Bahamas and Cuba



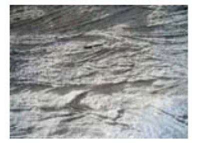
SE Cuba Carbonate Shoals Tidal Channeling

Long Island Ooid Shoals Tidal Channeling



Applications of Field Desciptions

Field descriptions of prograding and accumulating carbonate grainstone wedges and sheets lend themselves to process modeling. These models can be applied to comparable grain carbonates associated with subsurface plays in the Middle East and the Gulf Coast of the USA. The mix of outcrop description with a plausible theoretical model has application to hydrocarbon exploration and reservoir modeling. This study when it is completed will be used by those who are in the oil patch trying to extend and model hydrocarbon reserves.



Pleistocene oolitic grainstones on West Caicos

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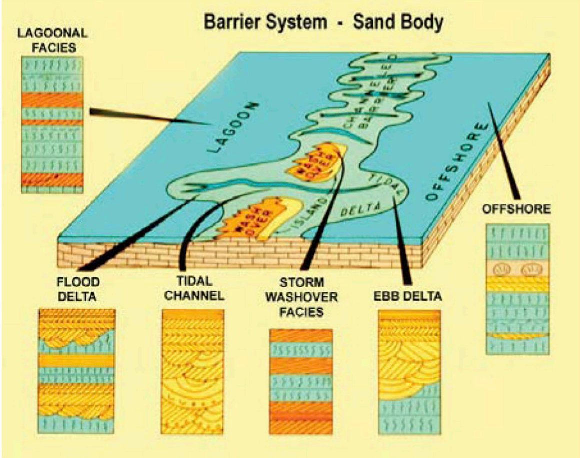
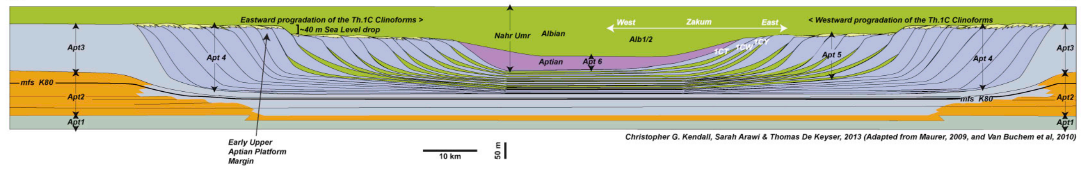
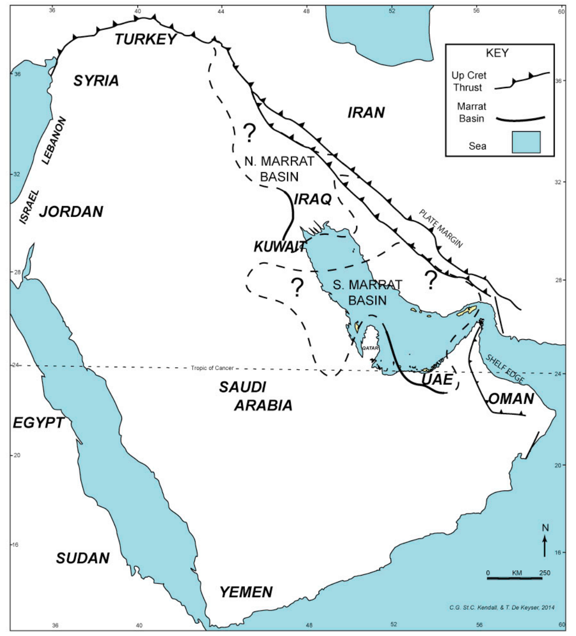


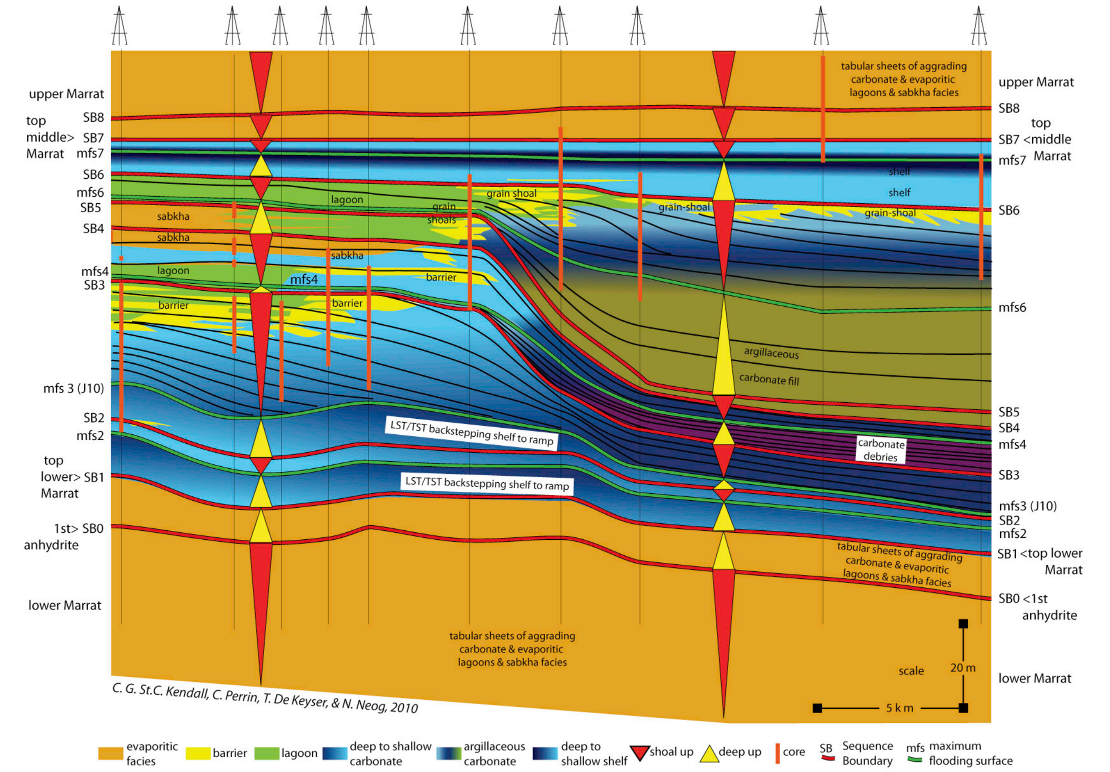
East West Cross Section of the Bab Basin for the Aptian to Early Albian

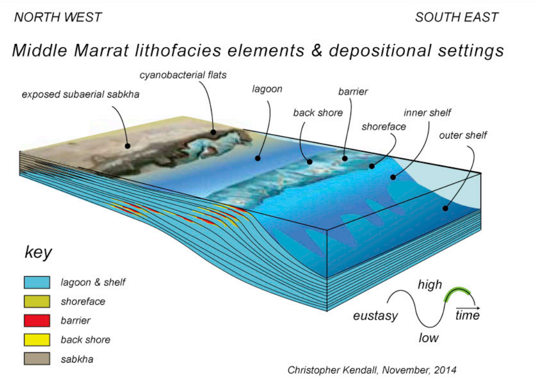


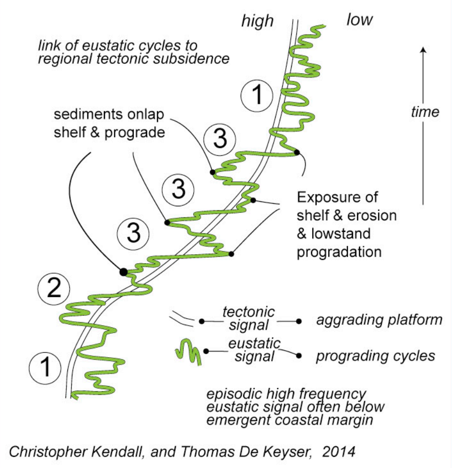
Approximate Location of middle Marrat ISBs

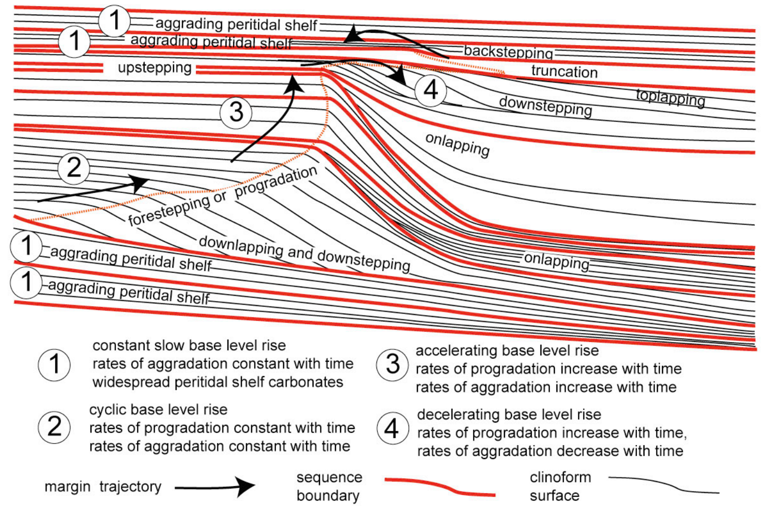


NW - SE Sequence Section of middle Marrat - Flattened at its Top

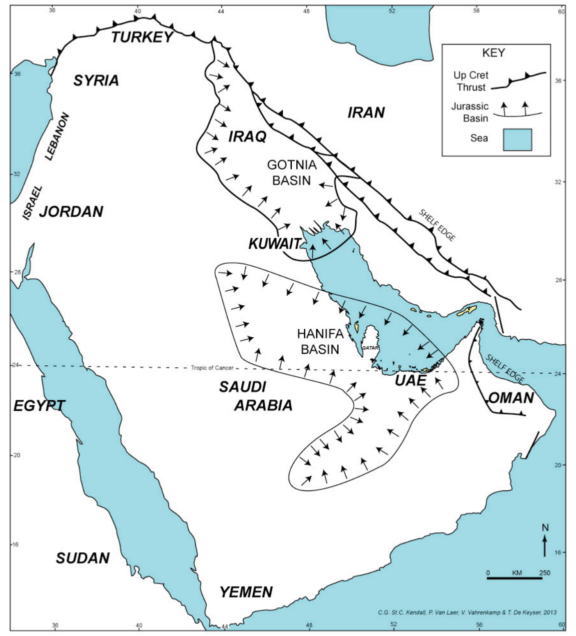




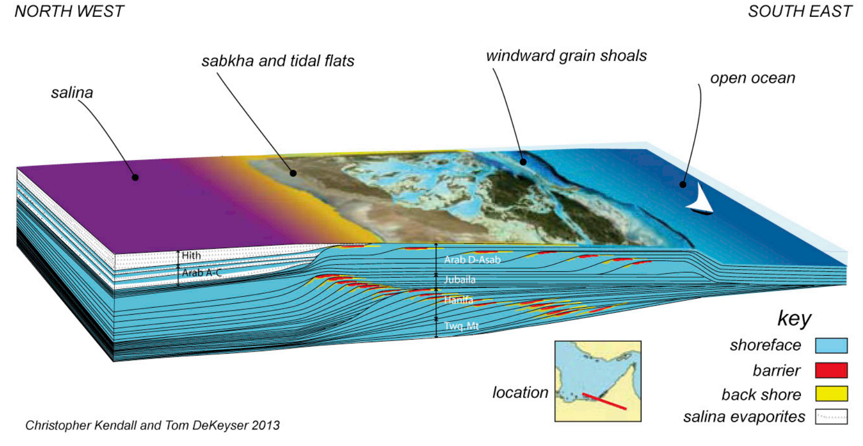




Hanifa Formation ISBs



Hanifa ISB Middle to Upper Jurassic facies & depositional settings



Conclusions

The simulations suggest that the driving mechanisms behind accommodation, though model dependent, are the product of both a varying eustatic driver and an equally important varying tectonic driver. Both eustasy and tectonic subsidence appear to have moved in and out of phase with each other. In the simulation, portions of the cyclic sedimentary section are produced when tectonic subsidence was more rapid and eustatic accommodation lay above the depositional surface, but when the rates of tectonic accommodation were slow, then eustatic sea level dropped below the carbonate depositional surface and periods of exposure ensued.

An argument against such a model might be a lack of diagenetic evidence of "long" exposure but radiometric dating of the sedimentary section support the long periods of time involved, though carbonates show evidence of only short lived exposure. Our conclusion from running the simulations is that both eustatic and tectonic accommodation rates vary between both rapid and slow.

In examining sedimentary sections it is often assumed that much accommodation is the product of slow tectonic movement, which was slow and steady, but the simulations and sediment geometries show the rates periodically changed. This hypothesis is supported by the conceptual models that are the building blocks of the regional geology and the simulations.