# PS Analysis of Sequence Stratigraphic Models for the Jurassic Cretaceous Sedimentary Fill of the Intrashelf Basins of the Eastern Margin the Arabian Plate\*

Christopher G. Kendall<sup>1</sup>, Phil Moore<sup>1</sup>, Enrica Viiparelli<sup>2</sup>, Thomas L. De Keyser<sup>3</sup>, Abdulrahman Alsharhan<sup>4</sup>, and Cameron Kloot<sup>5</sup>

Search and Discovery Article #30326 (2014)\*\*
Posted April 21, 2014

#### **Abstract**

Two critical conceptual sequence stratigraphic models for exploration and production were analyzed with sedimentary computer simulations of the Jurassic and Cretaceous sedimentary fill of the Intrashelf Basins (ISB) of the Eastern margin the Arabian Plate. One tracked the Hanifa Basin fill from Jurassic argillaceous carbonates to evaporites to the Cretaceous carbonates and the other the Aptian/Albian fill of the Bab ISB during a glacially induced sea level low. The Hanifa ISB simulation demonstrated Lower to Middle Jurassic sediments onlapped the uplifted eastern plate margin of the UAE and Oman as carbonates prograded and filled westward. Uplift ended Middle Jurassic accumulation with subaerial and progressive erosion of the Tuwaiq and Dhruma Formations on the eastern plate margin. Margin collapse caused a drowning unconformity. Westward of the platform margin the intra-shelf basin a base-level fall accompanied Arab and Hith evaporites accumulation. In the Early Cretaceous, the platform extended to North Oman with deposition of argillaceous hemipelagic carbonates of the Habshan. The lack of evaporites supports a climatic change from the Jurassic arid climate to a Cretaceous humid one. The simulation of the Mid Cretaceous carbonates supports division into Early Aptian and Late Aptian carbonate platform second order supersequences that aggraded and prograded to fill the Bab ISB. An unconformity initiates the sequence with westward prograding lowstand clinoforms onlapping eastward onto the Lower to early Upper Aptian carbonate platform of the SW margin of the Bab ISB. The simulation captures an initial sharp sea-level drop of 35–40 m from the early Upper Aptian shelf break to the topset of the first lowstand clinoform, and the sea-level drop by another 10 m during the progradation of following eight clinoforms. Each progradational pulse of the clinoforms is modeled over 405 k.y. Simulation illustrates the initial sharp sea-level drop of some 40 m followed by continued slow sea-level fall producing lowstand clinoforms prograding towards the ISB. Sedpak, developed at the University of South Carolina assumes clastic transport based on slopes and carbonate production based on water depth. 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.

<sup>\*</sup>Adapted from poster presentation given at AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014

<sup>\*\*</sup>AAPG©2014 Serial rights given by author. For all other rights contact author directly.

<sup>&</sup>lt;sup>1</sup>Earth Sciences and Resources Institute, University of South Carolina, Columbia, South Carolina, US (kendall@geol.sc.edu)

<sup>&</sup>lt;sup>2</sup>Earth and Ocean Sciences, University of South Carolina, Columbia, South Carolina, US

<sup>&</sup>lt;sup>3</sup>Civil and Environmental Engineering, University of South Carolina, Columbia, South Carolina, US (<u>dekeyser@wispertel.net</u>)

<sup>&</sup>lt;sup>4</sup>Technically Write Consulting, LLC, Harrisburg, Oregon, US

<sup>&</sup>lt;sup>5</sup>Middle East Geological and Environmental Establishment LLC, Al Ain, United Arab Emirates

### Simulation and analysis of sequence stratigraphic models for the Jurassic Cretaceous sedimentary fill of the Eastern margin the Arabian Plate

Christopher G. Kendall<sup>1</sup>, Phil Moore<sup>2</sup>, Enrica Viparelli<sup>3</sup>, Abdulrahman S. Alsharhan<sup>4</sup>, Tom De Keyser <sup>5</sup>, and Cameron Kloot

#### ABSTRACT

Critical conceptual sequence stratigraphic models for exploration and oroduction can be analyzed with sedimentary computer simulations of sedimentary fill of the intrashelf basins of the Eastern margin of the Arabia

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 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 Lowe Results for the Marrat and Hanita Basins simulations demonstrate the Low to Middle Jurassic onlapping the upliftled Arabian plate margin in Kuwait, Saudi Arabia, the UAE and Oman as two phases of carbonate margin progradation and basinward infilling. The Middle Jurassic ended with uplift and subaeralis 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 a base-level fall accompanied Arab and Hith evaporites accumulation

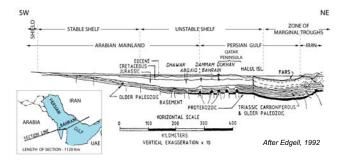
In Early Cretaceous times the platform of the Arabian Sheild extended to In Early Createctors times the placetors from the Auditor National Advantage North Oman with deposition of argillaceous hemipelagic carbonates of the Habshan. The lack of evaporites supports a climatic change from the arid climate 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 south-western margin of the Bab intrashelf basin and its Lower to early Upper Aptian carbonate platform. The simulation captures the initial sharp sea-level carbonate platform. The similation captures the initial shall p sea-level did of 35–40 m from the early Upper Aptian shelf break to the topset of the fin lowstand clinoform, and the sea-level drop by another 10 m during the progradation of following eight clinoforms. Each pulse of progradation of the clinoforms is modeled over 405 k.y. 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

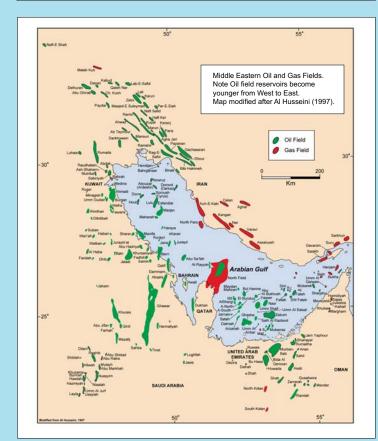
The Sednak sedimentary simulation, developed at the University of South clastic transport based on slopes. Output geometries display a sequence stratigraphic framework of erosional and depositional surfaces of the simulated section enabling the extension of interpretation of depositional setting and predictions of lithofacies geometries away from well data. This aids prediction of facies likely to contain both hydrocarbon and water

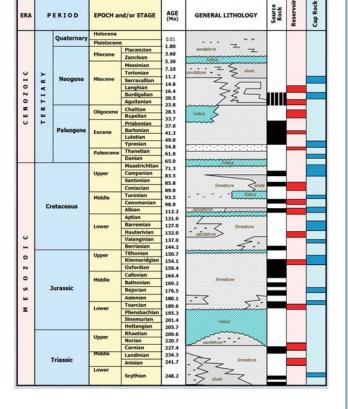
The advantage of these simulations is that it provides a template to the

complexities of sediment stratigraphy; enabling identification, testing, and modeling of sedimentary systems and the sharing of data with others; enhancing the understanding of biostratigraphy and providing age constraints for stratal geometries and sequence stratigraphic interpretations. They reduce time for understanding interpretations of seismic and well data by identifying and constraining key factors that control sequence stratigraphic geometries and architect rates of sedimentation, eustatic sea level, and tectonics.



Geological Cross Section of the Arabian Gulf Basin of sedimentary section overlying the Halokinetic Proterozoic Hormuz Series. The younger Paleozoic to Mesozoic to Teriary 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**

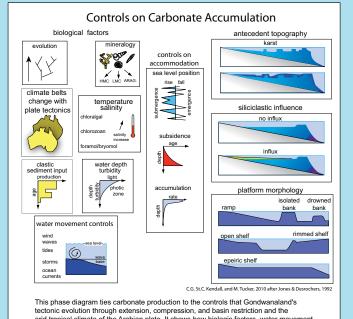
The region outlined by the red oval traces the evolution of the Southern Tethys basin seaway that has existed since the Precambrian This body of water flanked what is now the Arabian Plate and includes the proto Tethys, paleoTethys, and neoTethys Oceans. The evolving geographic location of this ocean and the geology that underlies it is responsible for the ccumulation 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 hese 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 U Cretaceous - L Tertiary 2.8% M - U Miss. 0.4% U Devonian - L Miss. 8% Silurian 9% U Proterozoic 0.2 %

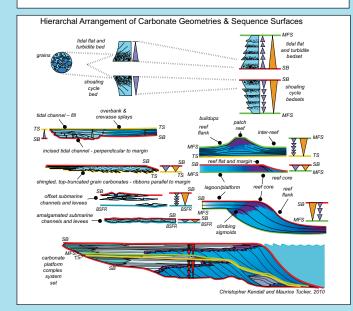
While Gondwanaland evolved through extension, compression, and basin restriction this also had impact on source rocks. Concurrently climate of the Arabian plate was affected by latitude rain shadow and as illustrated above green house and ice house climatic events and effects of transgressions and super-plumes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

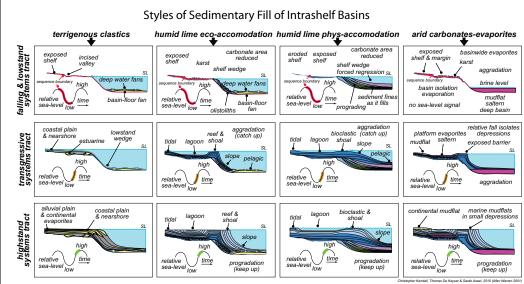
### **Organic Matter and Plate Tectonic Evolution of Arabian Gulf**

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 of seen 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.

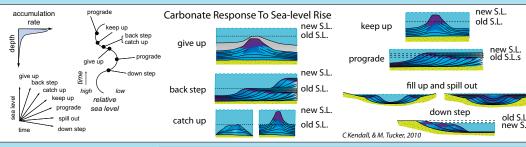


arid tropical climate of the Arabian plate. It shows how biologic factors, water movement and pre-existing topography were controls too within the intrashelf basins (ISBs)

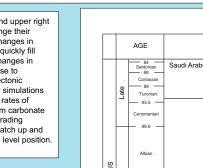


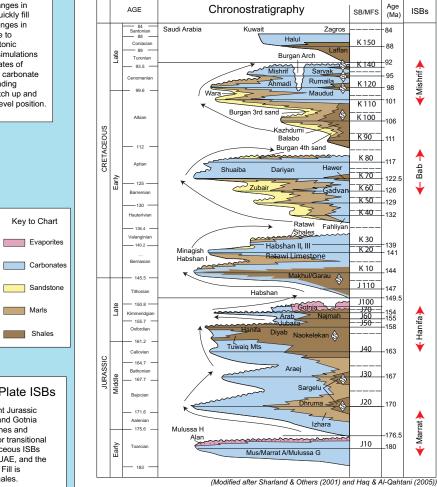


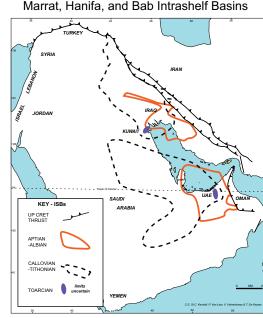
Following a low ISB development begins with a rapid sea level rise, exceeding carbonate production across platform interior, followed by aggradation on margin with a starved basin center. ISB margin then progrades and infills the basin, commonly less than 100 m deep.

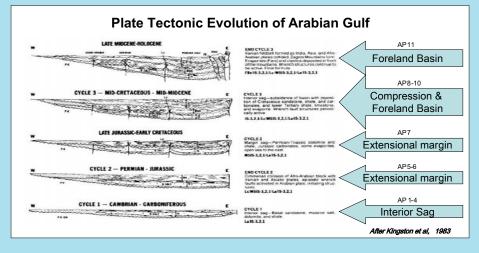


In diagrams to upper left and upper right carbonate geometries change their character in response to changes in any space generated by changes in base level (either a response to changes in eustasy or in tectonic subsidence). Sedimentary simulations varying accomodation and rates of sediment accumualtion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

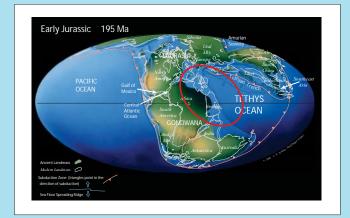


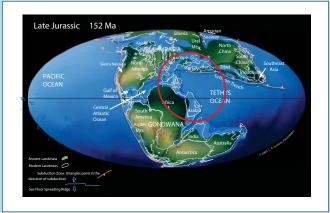






The stratigraphic framework of the Arabian Plate (AP) margin is subdivided by eleven major unconformity surfaces bounding tectonostratigraphic mega-sequences (AP 1-11 of Sharland et al 2001). These were created during low-frequency tectonic events associated with cycles of tectonic plate motion (Wilson, 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 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 adiacent to the southern shore of the Tethys Ocean. These barriers accumulated sediment over them and limited access to the sea. This lead to the punctuation of the geological record with evaporities, carbonates and source rocks associated with an adjacent arid climates. 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 surroundin subcontinents of Arabia and Africa.

### Chronostratigraphic Chart for Arabian Plate ISBs

As indiacted 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 Irag. 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.

### Introduction to SEDPAK

The computer simulation sedimentary SEDPAK was developed at the University of South Carolina as a simulation tool that models the geometry of the generalized lithofacies of a basin, resulting from the interaction between the major geological processes including:

Eustatic Sea Level Tectonic Movement Sediment Accumulation

SEDPAK constructs empirical models of sedimentary geometry. These sedimentary geometries are created by the infilling of a two dimensional basin from both sides with a combination of in situ carbonate growth and clastic sediment in the 15 steps outlined to the right.

Intuitive model input parameters are based on physical processes, including clastic transport based on depositional distance, quantity and slopes and carbonate production based on water depth. Data entry is accomplished by using a graphical user interface. Values are entered for the initial basin configuration and, as a function of time, the following variables may be specified: local tectonic behavior, sea level behavior, amount and direction of clastic deposition, accumulation rates of carbonates both as a function of water depth and pelagic accumulation. The model traces the evolving geometries of clastic and carbonate sediments through time, responding to the depositional processes previously itemized. Sediment geometries are plotted as they are computed, so the results are viewed immediately. Based upon these observations, parameters can be changed interactively and the program rerun until the resultant geometries are satisfactory.

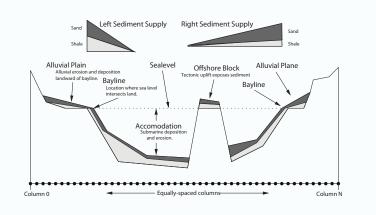
Rates of both carbonate and clastic sediment accumulation and transport distance down slope are modeled in two dimensional simulation space, and offer valuable insight into a more quantitative modeling approach. Further information on the fabrics of the deposits can be obtained by means of coupling computer models of sedimentary geometries with physically based submodels that describe the spatial and temporal evolution of relatively small portions of the entire system.

Output geometries display a sequence stratigraphic framework of erosional and depositional surfaces of the simulated section.

The origins of sediment geometries and facies are interpreted by comparison with observations of similar features in modern sedimentary systems and their processes and then the interpretations are tested with the SEDPAK simulation. The question is: do input parameters match those inferred from current field observations parameters set to create basic sequences stratigraphic systems tracts, including prograding low-stand and highstand systems tracts, and retrogradational transgressive systems tracts? The same applies to in-situ carbonate accumulation. Are the depth-production rates reasonable?

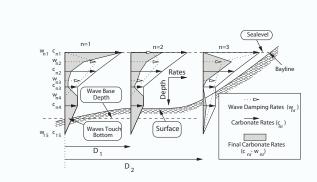
Computer modeling of sedimentary geometries that match interpreted sections is a repetitive exercise in parameter estimation, viewing of resulting geometries and adjusting of parameters to converge on a best match.

SEDPAK extends interpretation of depositional setting and predictions of lithofacies geometries away from the studied areas. It aids prediction of facies likely to contain both hydrocarbon and water resources and their characteristic fabrics.

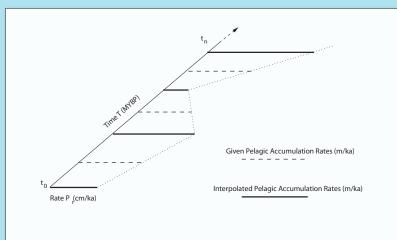


Basin Setting. The basin is divided into equally-spaced columns. After the bayline is located, alluvial sediment is eroded landward then submarine sediment is deposited or eroded. Offshore blocks created by sea level change or tectonic adjustments may be eroded to the initial basin surface.

STEPS 1 through 6



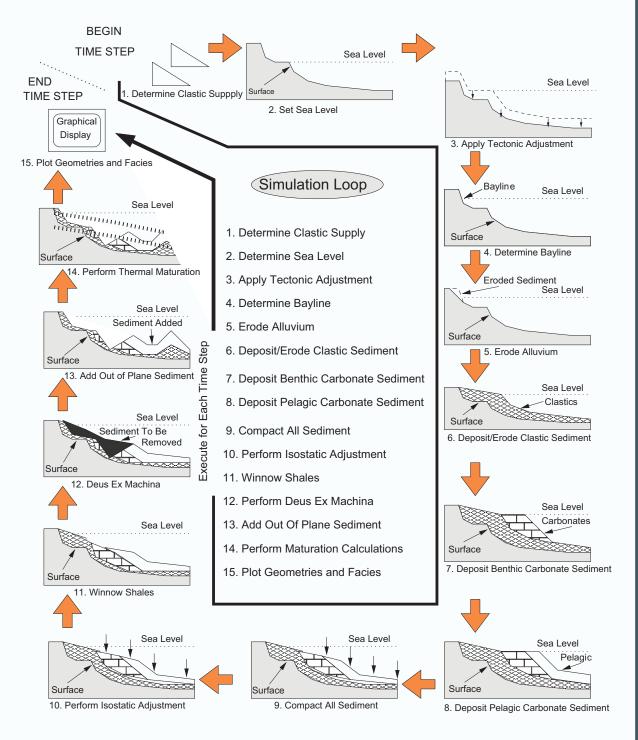
Winnowing of shale by waves. Waves touch bottom at left (n=1). The winnowing curves specify the percentage of shale to remove from the sediment column to the right of wave base.



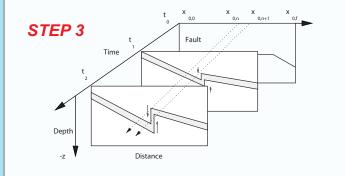
Pelagic deposition of Carbonates. Pelagic rates in meters/Ka can vary over time and are linearly interpolated between user defined rates at specific times.

STEP 8

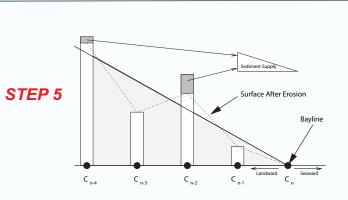
## SEDPAK Time Step Operations



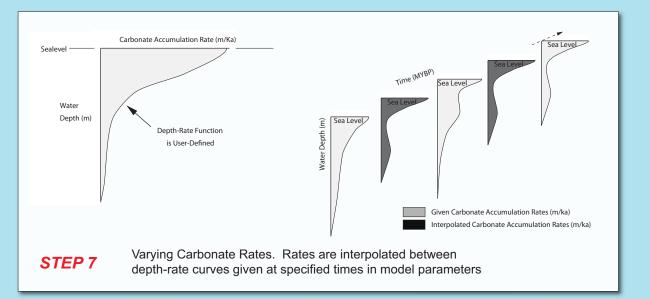
Within each time step, a fixed sequence of operations creates or modifies the sedimentary geometries. First, tectonic adjustments change the accommodation at points defined by the user across the basin. Next, the intersection of the sea level position with the basin surface defines a bayline location (Posamentier and Vail, 1988) marking the base of the alluvial plain. Sediment eroded landward from the bayline location is added to the sediment supply. Seaward of the bayline, sediment erodes or is deposited according to geometrical rules. After clastic deposition is completed, carbonates accumulate in-situ to form reefs. From the reef positions, excess carbonate is transported downslope as talus or turbidite, or backslope as lagoonal sediment. Next, a pelagic drape, specified as a rate, blankets the submarine setting. Sediment loading and compaction adjustments, followed by winnowing of shales, and out-of-plane erosion and deposition complete the operations for the time step. These operations are summarized by the 15 steps are represented above diagramatically.

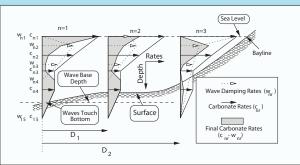


Vertical Fault Displacement. A vertical fault begins at time t The vertical arrows show displacement occurring between two adjacent columns over time.



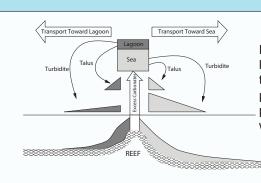
Schematic representation of Erosion. Sediment above the erosional line at columns Cn-2 and Cn-4 is removed. No sediment is eroded from Cn-1 or Cn-3. Eroded sediment is returned to the sediment supply for later deposition.





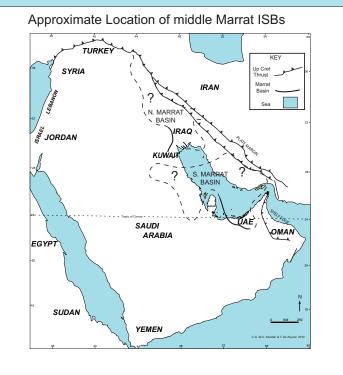
Wave damping of carbonate accumulation. From wave base in a landward direction to the right, wave damping rates (Wnr) are subtracted from the carbonate rates (Cnr) where n is the distance from wave base and r is the rate at that distance

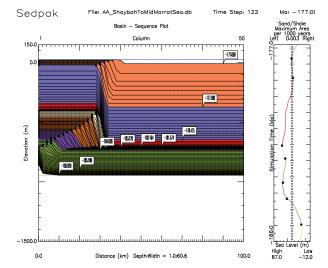
STEP 7



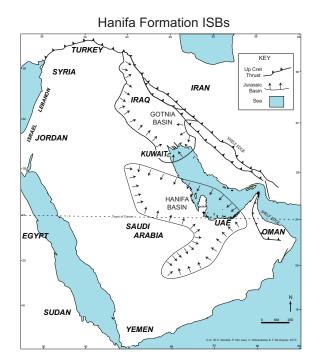
Excess carbonate production is bypassed in the lagoon and basin. A proportion of the excess is transported either into the lagoon or basin as a percentage. For each proportion, another percentage can be specified as talus or turbidites with specified distance of penetration.

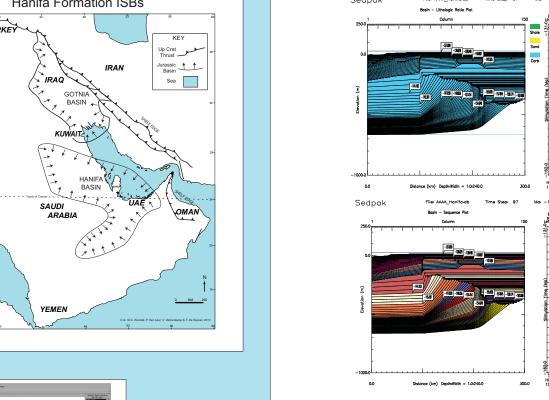
STEP 7





Simulated sedimentary fill of the Marrat basin used the sea level curve proposed by Hag et al 2012 for the lower Jurassic. There was sea level high from -182 to -177 MYBP. Prior to the eustatic rise contemporaneous platform carbonates filled the carbonate platform but post -182 carbonates formed clinoforms whose trajectory changed from horizontal to vertical while carbonates accumulated down slope from sea level to the deepest portions of the basin at around 150 meters. This sedimentary fill was a mix of carbonate and shale. Around -177 MYBP rates of eustatic sea level rise slowed while carbonate accumulation filled the basin and prograded out from the basin margin.





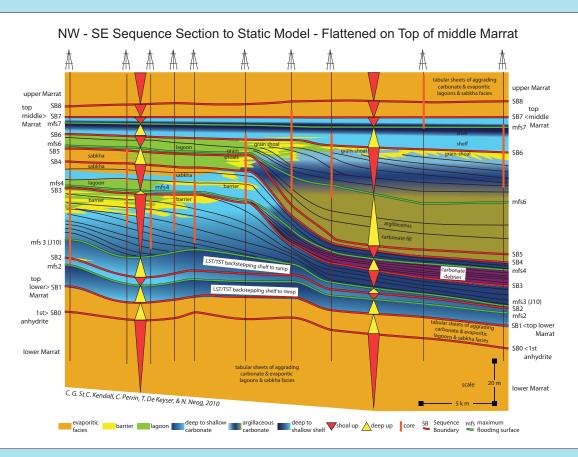
Major Conclusion

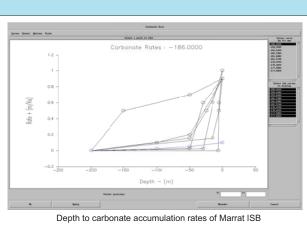
Simulations support mix

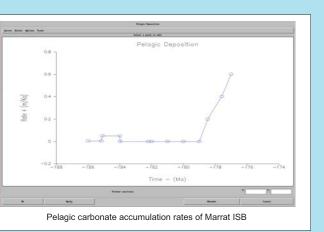
of tectonic subsidence

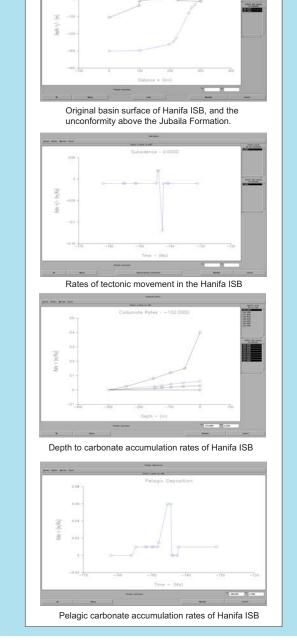
and eustasy as source of accomodation.

Sedimentary fill of Hanifa basin was simulated by modeling the accommodation by varying eustasy with the Haq et al 2012 curve for the Middle and Jurassic conjunctly modulated by varying tectonic subsidence during accumulation of the Jubaila Formation. Eustasy progressively rose from -161 to -144 MYBP as the prograding Tuwaig Moutain Group filled the basin. At -143.76 tectonic accommodation was reduced and sea level fell below the basin margin followed by a rise in relative sea level and the Jubaila Formation onlappping the margin. This was followed by a drop in sea level the exposed the shelf and eroded this and then by further eustatic rise when contemporaneous platform carbonates filled the carbonate platform crest with a horizontal trajectory. Carbonates accumulated to sea level and prograded both east and westward from the basin margin crest. To the east the Hanifa basin then filled with evaporites

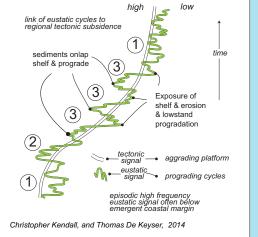


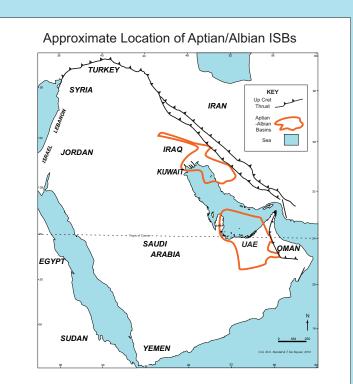


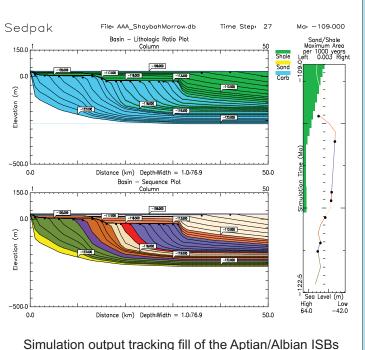




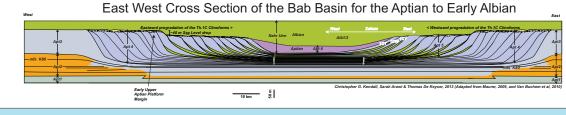
## Hanifa ISB middle to upper Jurassic facies & depositional settings NORTH WEST SOUTH EAST sabkha and tidal flats shoreface barrier \_\_\_\_ back shore salina evaporites

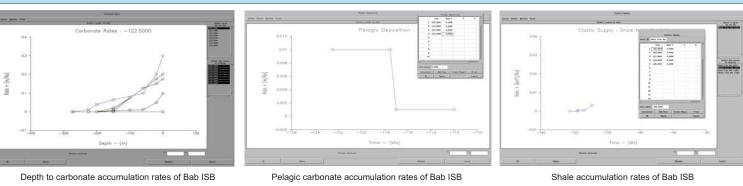






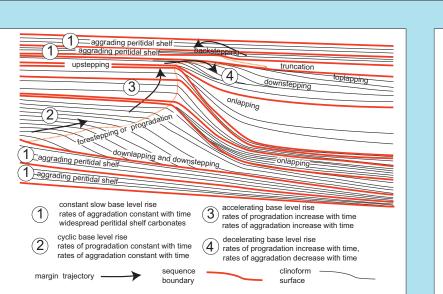
Simulation output tracking fill of the Aptian/Albian ISBs





### Simulation results of the fill of the Aptian/Albian ISBs

Simulated sedimentary fill of the Bab basin used the sea level curve proposed by Maurer et al 2012 for the Aptian Albian. These authors proposed a glacially induced sea level low from -117 to -113 MYBP. Prior to the eustatic fall contemporaneous rudist rich carbonates formed clinoforms that accumulated down slope from sea level to the deepest portions of the basin at around 200 meters. This sedimentary fill was close 100% carbonate but following the sea level low at -117 alternations of shale and carbonate filled the basin margin. Around -113 MYBP in the mid Albian eustatic sea level rose while carbonate accumulation fell and the Wasia calcareous shale filled and onlapped the basin margin.



### 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 eustatic accommodation lies above the depositional surface, but when the rates of tectonic accommodation are slow, then eustatic sea level drops below the carbonate depositional surface and long periods of often unrecognized exposure ensue.

An argument against such a model might be the lack of diagenetic evidence of long exposure but one finds sections of sedimentary rock that from radiometric dating suggest long periods of time are involved in the creation of carbonate sections which show only evidence of short lived exposure. Our conclusion from running the simulations is that both eustatic and tectonic ccommodation may be both rapid or may be slow.

Often the easy out, when looking at sedimentary sections, is to assume that the rate of tectonic movement was slow. However the simulations argue against this. Never the less it has to be accepted that this is an unprovable hypothesis, though from our point of view this is an elegant proposal even though conceptual models are the building blocks of the simulations.