3D Forward Stratigraphic Modeling in Reservoir Quality Prediction – Arab-D Reservoir, Ghawar Field, Saudi Arabia*

Rainer Zuhlke[1], Dave Cantrell[1], Robert F. Lindsay[1], and Yousef Mousa[1]

Search and Discovery Article #20325 (2015)**
Posted October 19, 2015

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

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Abstract

Carbonate reservoirs are characterized by significant heterogeneity at the regional to inter-well scale. Reservoir quality predictions (RQPs) based on geostatistical and object-based modeling approaches contain additional uncertainties in carbonates compared to siliciclastic reservoirs. Process-based, forward stratigraphic modeling (FSM) offers high potential for improved RQP with reduced risk in exploration and improved recovery in production. FSM tools and workflows have been used for RQPs in the Arab-D reservoir (Lower Jurassic) in the Ghawar field. Data quality and coverage are exceptional with wells spaced at short distances. While effective porosities and permeabilities are generally high, marked lateral and vertical heterogeneities occur in this homoclinal carbonate ramp setting. They are related both to depositional facies with small-scale paleogeography and diagenetic overprint, e.g., dolomitization. FSM for RQPs in the Arab-D has been performed at a regional scale (270×180 km, cell size 2,000 m, time step 5 ka). Models are calibrated to 11 key wells and detailed depth/thickness grids from several hundred wells. The model has been tested by comparing virtual wells generated from the FSM to real-world wells, which were not included in the input database. Both Navier-Stokes/Lagrangian and diffusion-based approaches have been applied. Over reservoir thicknesses of 1–3 m, FSM correctly predicts (textural) porosities with errors of ±3 pu. Modeled depositional facies, e.g., skeletal-oolitic grainstone/rudstones and stromatoporoid packstone/ grainstone/boundstones with high porosities closely match core and log data. Vertical stacking patterns, e.g., parasequence sets and high-frequency sequences at the scale of 5–10 m resolution are predicted according to the actual subsurface data. In shallow subtidal to peritidal reservoir-prone settings, thickness uncertainties range between ±4 and ±10%. In more open marine settings (outer ramp to basin), uncertainties are higher and may reach up to ±28%. Input data and processes in these settings still require optimization. Current FSM studies focus on

the field to inter-well scale based on a rigorous sequence stratigraphic framework. They reach the resolution of individual flow units (parasequences, shallowing/deepening upward cycles). FSM may be coupled with other modeling approaches, e.g., reactive transport modeling for diagenesis and surfaced-based modeling for fluid flow.

Selected References

Handford, C.R., D.L. Cantrell, and T.H. Keith, 2002, Regional facies relationships and sequence stratigraphy of a super-giant reservoir (Arab-D Member), Saudi Arabia: in J.M. Armentrout, ed., Sequence stratigraphic models for exploration and production: Evolving methodology, emerging models and application histories, 22nd Annual Bob F. Perkins Research Conference: Gulf Coast Section SEPM, p. 539–564.

Lindsay, R.F., 2014, Rediscovering The Arab-D Reservoir: AAPG International Conference & Exhibition, Istanbul, Turkey, September 14-17, 2014. AAPG Search and Discovery Article 90914 (2014). http://www.searchanddiscovery.com/abstracts/html/2014/90194ice/abstracts/1948188.html.

Lindsay, R.F., D.L. Cantrell, G.W. Hughes, T.H. Keith, H.W. Mueller, and S.D. Russell, 2006, Ghawar Arab-D; widespread porosity in shoaling-upward carbonate cycles, Saudi Arabia: Abstracts: Annual Meeting - American Association of Petroleum Geologists, v. 15, p. 64.

Moore, G.T., L.C. Sloan, D.N. Hayashida, and N.P. Umrigar, 1992, Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: II. Sensitivity tests comparing three different paleotopographic settings: Palaeogeogr., Palaeoclimatol., Palaeoecol., v. 95, p. 229-252.

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Saudi Aramco

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Rainer Zuhlke, Dave L. Cantrell, Robert F. Lindsay, Yousef H. Mousa

Saudi Aramco, Dhahran

AAPG ACE 2015, Denver
06/01/2015, 8:45-9:05 AM
R. 601/603

Guideline

1. Geological Setting
2. Input Parameters
3. Forward Stratigraphic Modeling
4. Verification & Reservoir Prediction
5. Conclusions

Reservoir Stratigraphy

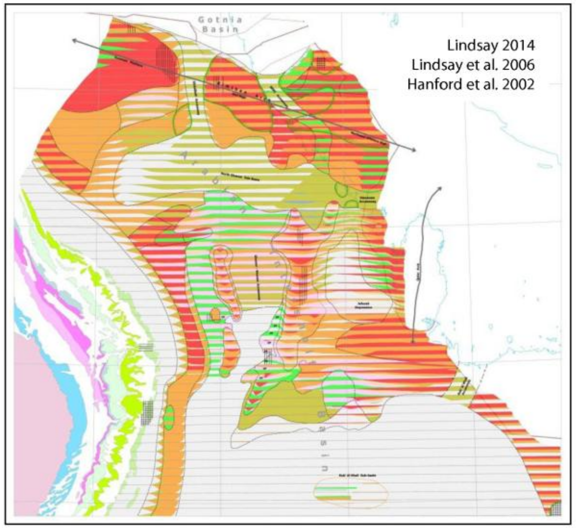
1. Geological Setting

- Arab-D Reservoir
  - Homoclinal carbonate ramps
  - Shelf-interior basins

  - 6 zones, 2 major reservoir zones
  - 14 standard lithofacies types
  - FSM: 5 combined lithofacies units

  - High-resolution sequence stratigraphy
  - FSM: parasequence (set) resolution

  - Outcrop-reservoir analogue study
  - See oral presentation: Jacquemyn et al. Wed, 06/03, 10:50 am, R. 605/607



Paleogeography Kimmeridgian

Tidal Flat, Lagoon	Inner Ramp
Oolitic Shoals	Ramp Crest
Clado. Mounds	Middle Ramp, proximal
Strom. Mounds	Middle Ramp, distal
Bio-/Intracl. P, W, M	Middle Ramp, distal
Bioclastic W, M	Outer Ramp & Shelf-Interior Basin

Presenter’s notes: The Arab-D reservoirs developed on the very wide continental shelf of the western Tethys. This highly detailed paleo-geographic map shows a highly complex pattern of oolitic shoals, stromalgal mounds, intertidal flats and shelf-interior basins. Maximum water depth on the shelf reached a few tens of meters, possibly up to 50-70 m in the intra-shelf basins.

Reservoir Stratigraphy

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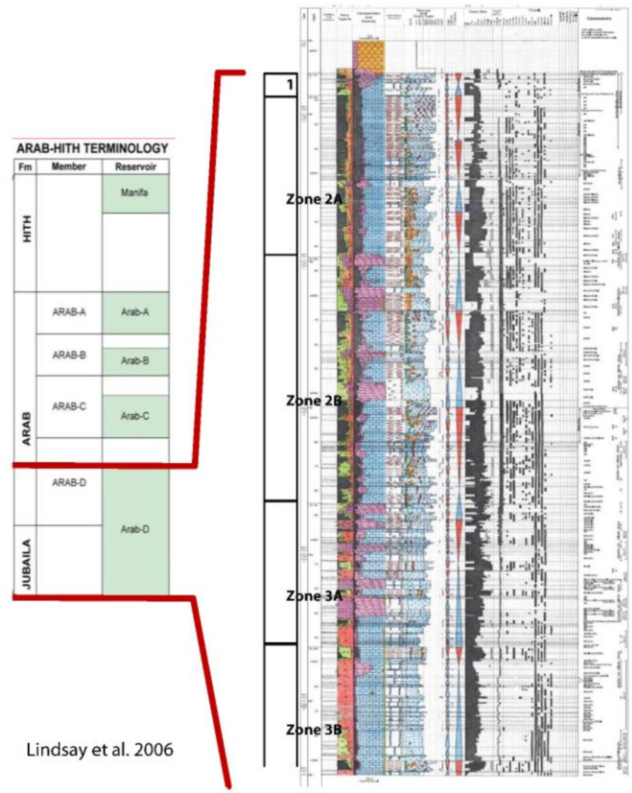
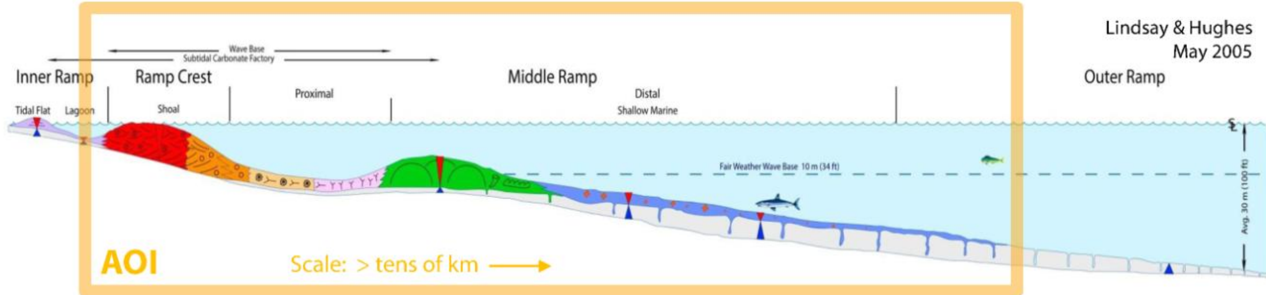


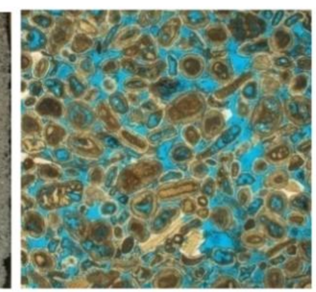
Lindsay et al. 2006

Presenter's notes: The Arab-D Formation is subdivided into six zones, two of which are the most important, thickest reservoir zones with excellent quality. Fourteen lithofacies types are subdivided. They have been lumped to five combined lithofacies associations for the sake of acceptable computing times. Reservoir architecture and internal heterogeneities have been studied at the resolution of single flow units and para-sequences. The resolution of specific in this presentation is reduced to para-sequence set resolution.

Depositional Environments

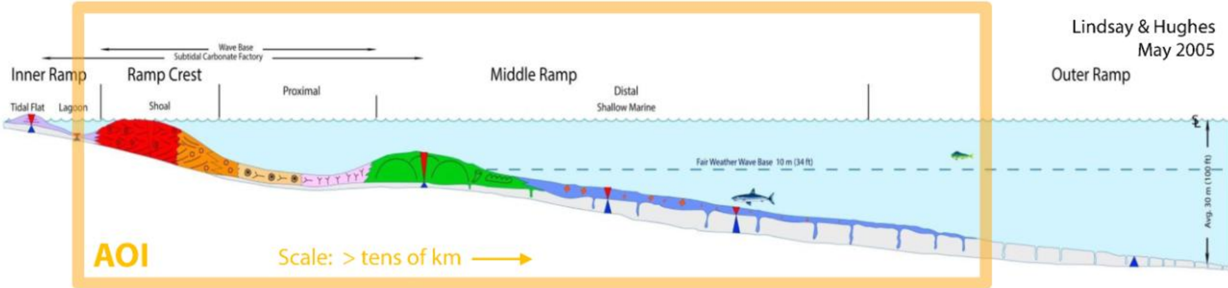


Oolitic Grain- &
Packstone



Presenter's notes: This is a generalized cross section through the Arab-D ramps. The most proximal environment in this model is oolitic shoals with excellent reservoir properties. Lindsay: skeletal-oolitic grainstone, mud-lean packstone, and some mud-rich packstone

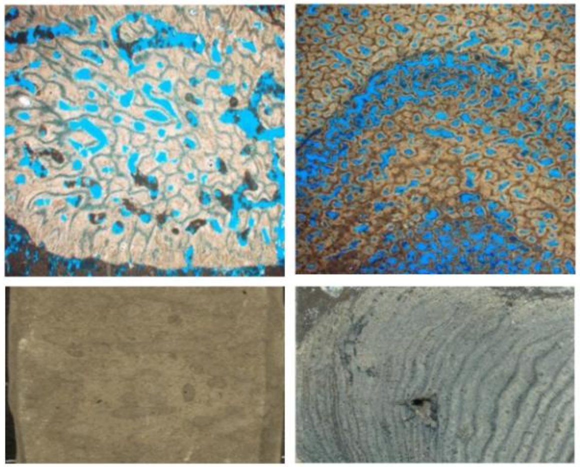
Depositional Environments



Oolitic Grain- & Packstone

Cladocoropsis Pack- & Grainstone

Stromalgal Pack-, Grain- & Boundstone

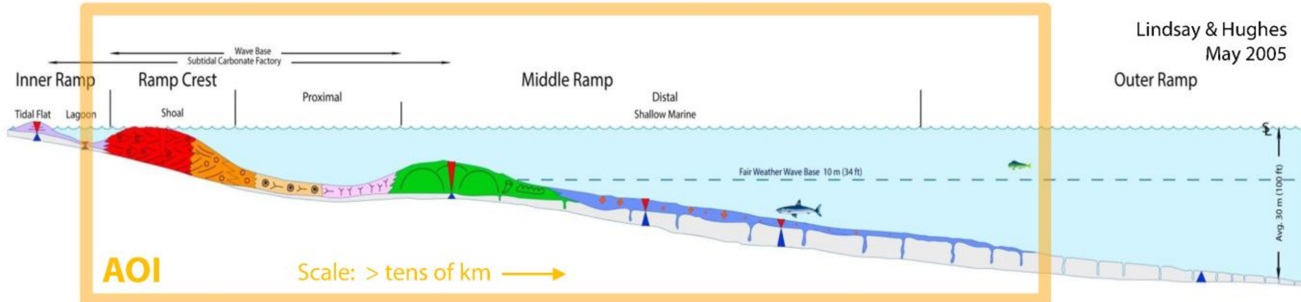


Presenter’s notes: Basinward follow *Cladocoropsis* and stromalgal mounds. *Cladocoropsis* are mound-building algae, specifically of *Siphonocladacaeae*.

Lindsay: stromatoporoid-red and green algae-coral rudstone and float-stone

Lindsay: *Cladocoropsis* rudstone and floatstone

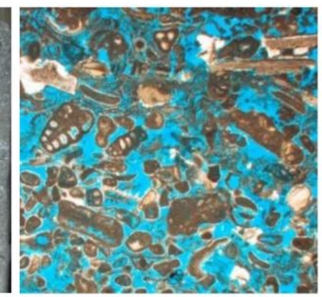
Depositional Environments



Oolitic Grain- & Packstone

Cladocoropsis Pack- & Grainstone

Stromalgal Pack-, Grain- & Boundstone

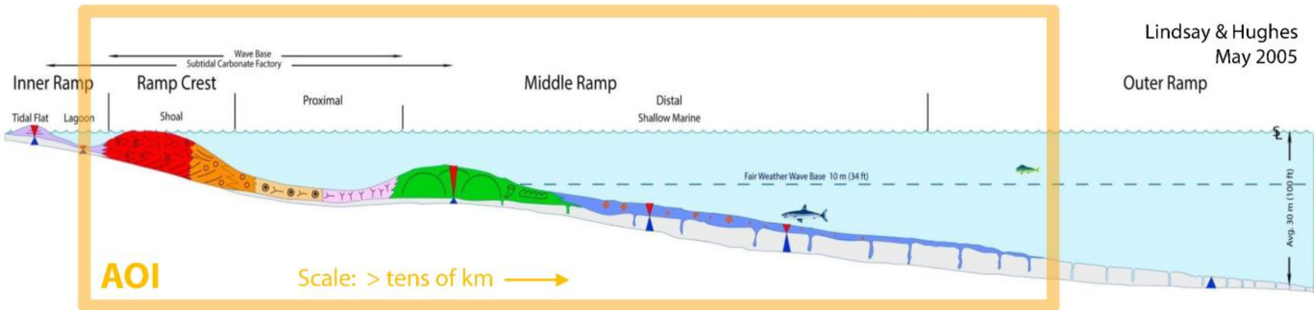


Bioclastic to intraclastic Pack-, Wacke- & Grainstone

Presenter's notes: The distal part of the middle ramps features bioclastic and intraclastic Pack- to wackestones, some grainstones. Lindsay: bivalve-coated grain-intraclast rudstone and floatstone

Depositional Environments

1. Geological Setting



Lindsay & Hughes
May 2005

Oolitic Grain- &
Packstone

Cladocoropsis Pack-
& Grainstone

Stromalgal Pack-,
Grain- & Boundstone

Bioclastic to intraclastic Pack-, Wacke- & Grainstone

Mud- to bioclastic Wackestone

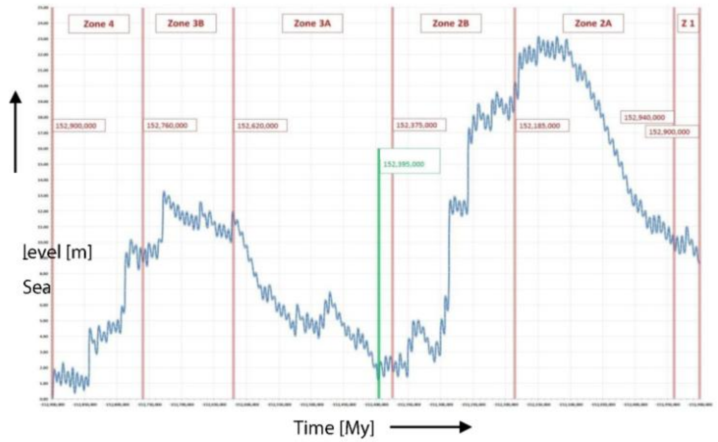
Presenter's notes: Finally, bioclastic mud- and wackestone were deposited on the outer ramp, the shelf interior basin.
Lindsay: micritic to very fine-grained deposits

Accommodation Space - Creation

2. Input Parameters

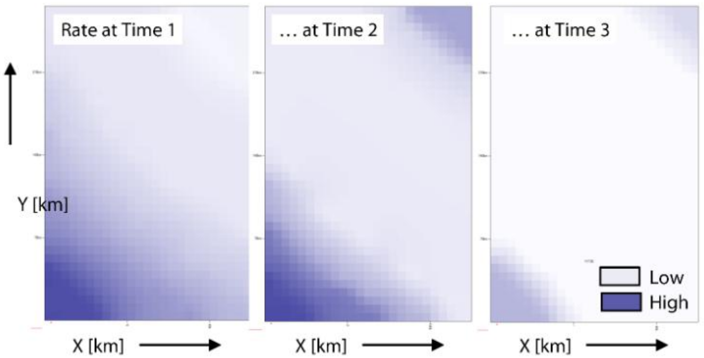
Sea-level Proxies

- Cyclostratigraphy
- Average cycle duration approx. 7 ka
- Arabian platform & Tethys sea-level
- Amplitude 20-25 m to m-scale



Subsidence

- 2D flexural inverse modeling
- Local & regional corrections in FSM
- Flexures with approx. 10-20 m offset
- Range 60-140 m/my



Presenter's notes: Input parameters. Let us look at selected input parameters for the reservoir modeling. Cyclostratigraphic analyses provide proxies for sea-level changes. While these analyses have their limitations, they provide the relatively best data on short-term and long-term sea-level fluctuations.

Accommodation Space - Creation

Sea-level Proxies

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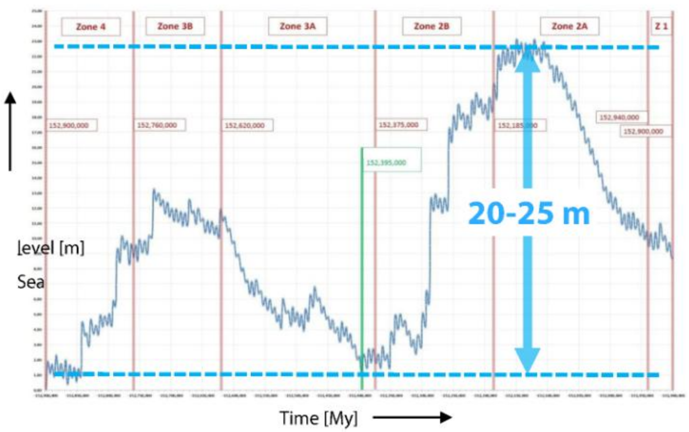
- Average cycle duration approx. 7 ka
- Arabian platform & Tethys sea-level
- Amplitude 20-25 m to m-scale



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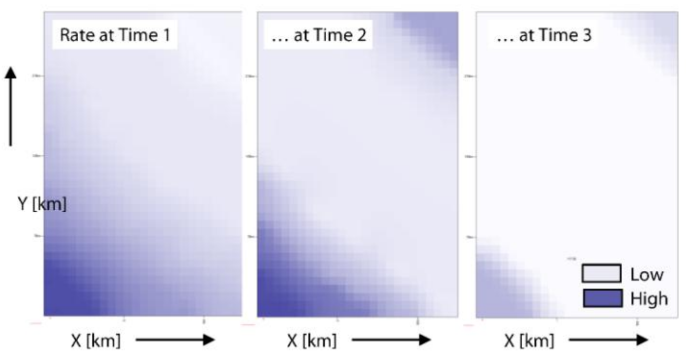


Presenter's notes: The maximum amplitude over 1 Ma reached 20-25 m. Although the Arab-D was deposited on a wide continental shelf top, small-scale lateral and temporal changes in subsidence controlled the small-scale paleogeography of the Arab-D shelf. Variations in subsidence reached rations of somewhat over 1:2. Syn-sedimentary faulting is largely absent in the AOI, gentle flexures prevail. Variations in subsidence are related to salt withdrawal in the subsurface or differential compaction.

Accommodation Space - Infill

2. Input Parameters

Lithologies

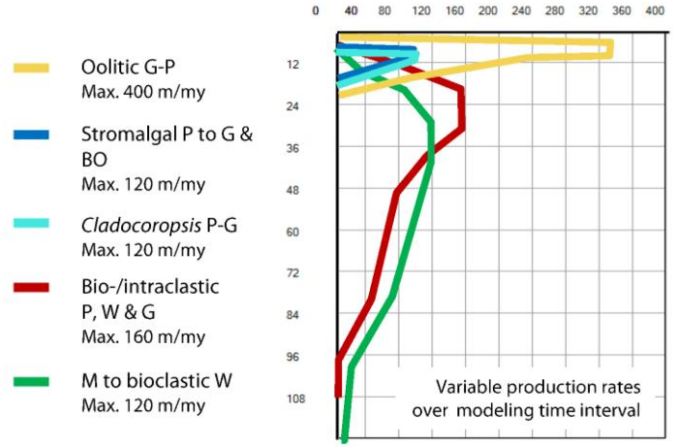
- 6 lithologies
- Production rates (depth, energy, time)
- Erosion and secondary transport
- Dissolution

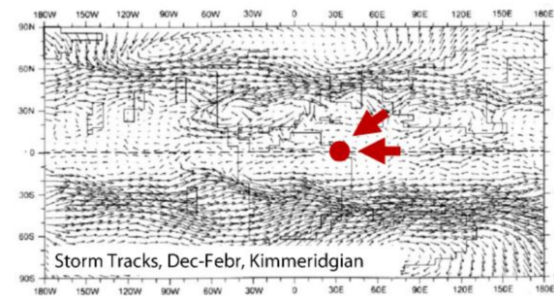
Paleo-Environment

- Short & long-term wave action
- Storm direction and frequency
- High-energy setting

Absolute Ages

- Biostratigraphy (benthic forams)
- Tied to Tethyan biostrat (ammonoids)
- Tied to Arabian plate sequence stratigraphy
- Time interval Arab-D Reservoir approx. 1 My





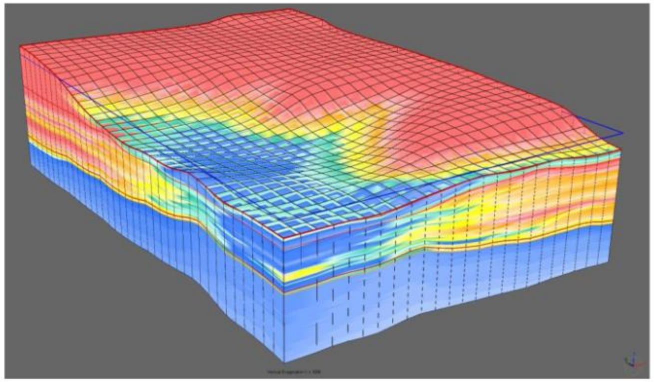
Moore et al. 1992

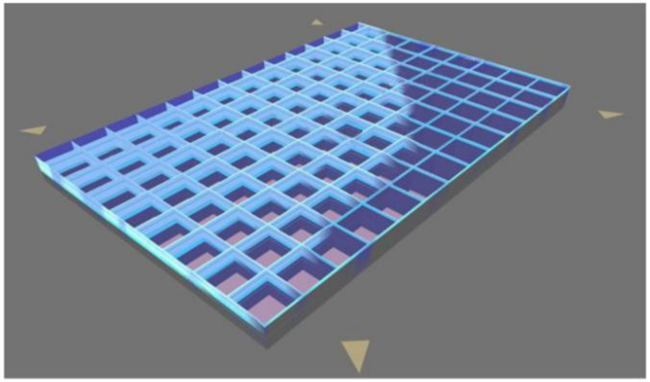
Presenter's notes: The original model considers 6 lithologies, 5 of which you will see in this model. Production rates vary in time and are depth- energy- and facies-dependent. The Arab-D was a high-energy environment with major storm activity and a fairly deep normal wave base of 10-15 m. The chronostratigraphic framework of the Arab-D is based on biozones tied to Tethyan time charts and sequence stratigraphic schemes. The overall duration of the Arab-D was in the order of 1 My.

Approach

3. Forward Stratigraphic Modeling

- Forward Stratigraphic Modeling (FSM)
  - Diffusion based
  - Navier-Stokes based
- Setup
  - Max. area of interest 270x180 km
  - Min. time step 5 ky
  - Max. cell spacing 1 km
- Calibration & Input data
  - 9 calibration wells
  - Regional data
  - Facies model
  - Climate model





Presenter's notes: Forward Stratigraphic Modeling. We have used two modeling approaches for forward stratigraphic modeling and reservoir prediction. Diffusion based, represented by Dionisos (IFP) and Navier-Stokes, represented by Sedsim (originally from Stanford University and CSIRO). This presentation will focus on the (Presenter's notes continued on next slide)

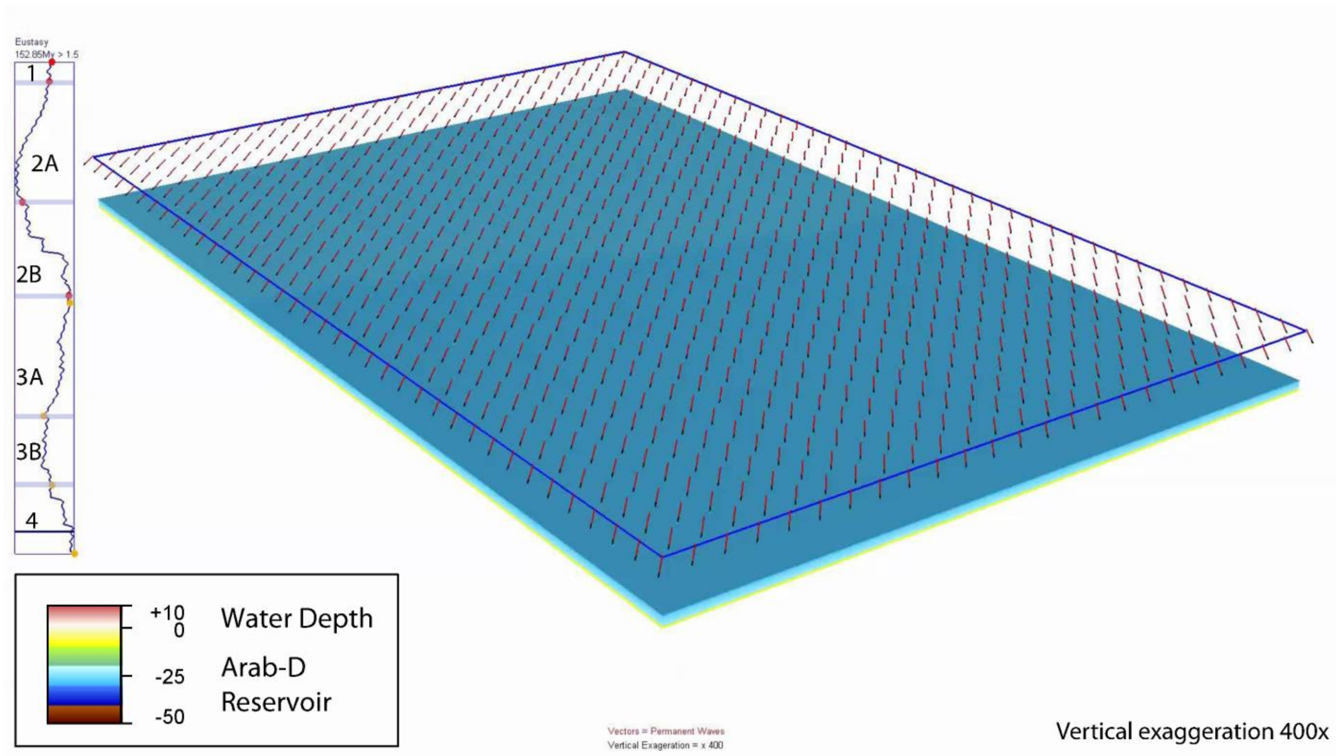
(Presenter’s notes continued from previous slide)

results from diffusion-based modeling.

The reasons this are entirely unrelated to the quality of the software or the predictions achieved by them. The area of interest covers up to 270x180 km (field scale in this case).
Minimum time step is 2 ky. Maximum cell spacing is 1 km. Input and calibration data come from nine key well which were cored throughout the Arab-D and additional data from other well logs, seismic data and climate models.

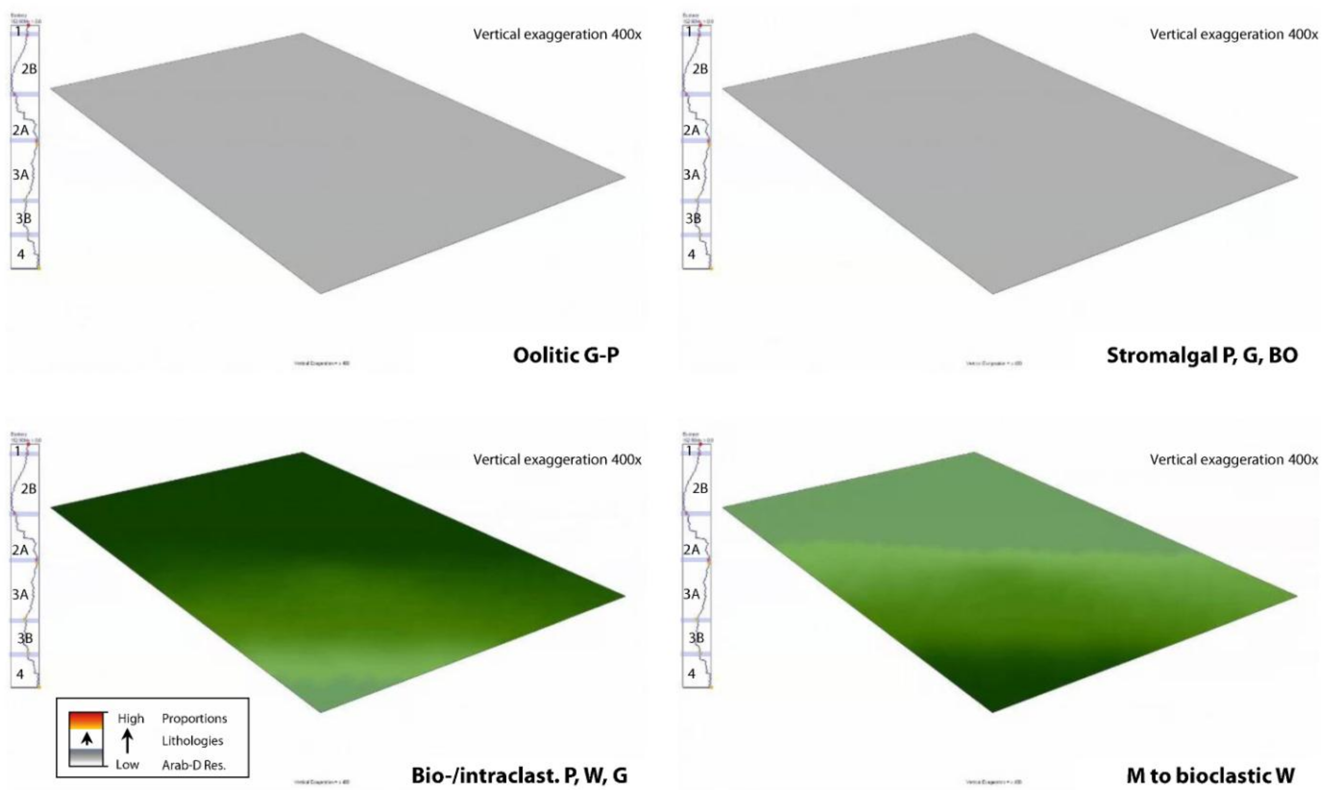
GDE / Water Depth

3. Forward Stratigraphic Modeling



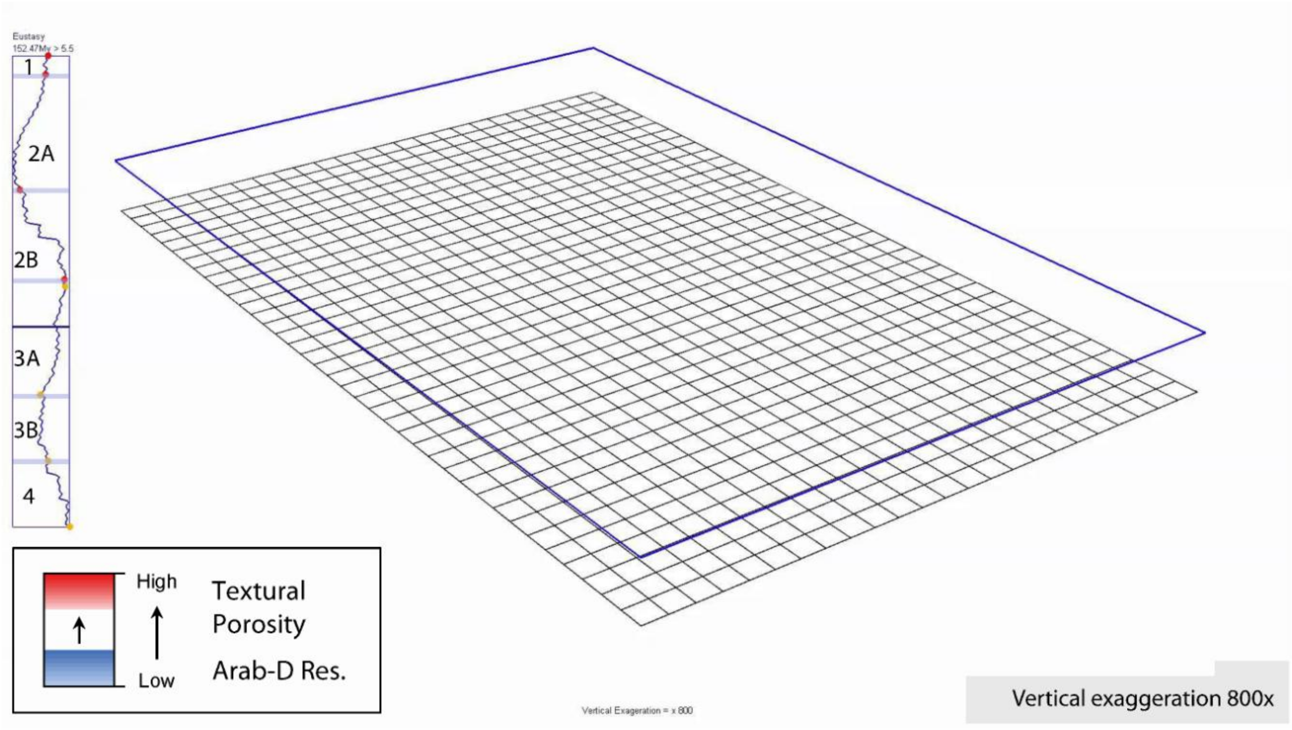
Presenter's notes: This the visualization for general depositional environments, represented by water depth. Reservoir zones to the left, AOI 270x180 km. Original resolution of the model has been reduced to a grid size of 7 km for presentation.

Lithologies

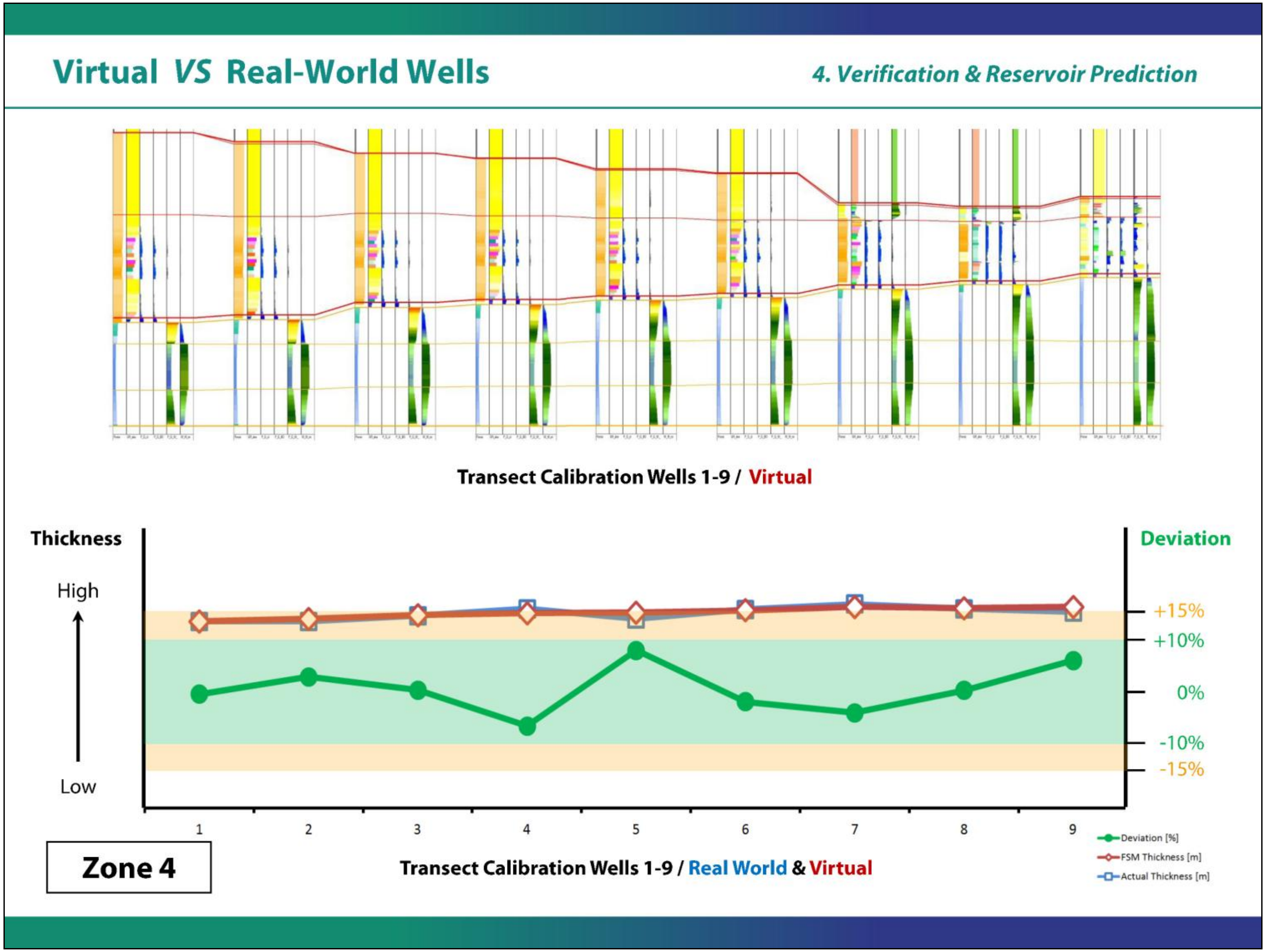


Presenter's notes: The four movies show the development of the Arab-D in the Area of interest for four selected lithologies. Grey colors indicate low amounts of the specific lithofacies, red colors high amounts. Upper left: oolitic grainstones. Upper right: stromalgal mounds. Lower left: bio-/intraclastic Wacke- to Packstones. Lower right: bioclastic Wacke- to Mudstone.

Porosity



Presenter's notes: This is the reservoir quality prediction for the Arab-D. Let me stress that porosity is textural porosity, not post-burial true porosity including diagenetic overprint and dolomitization. This requires integrated forward stratigraphic and reaction-transport modeling for cementation and dolomitization.



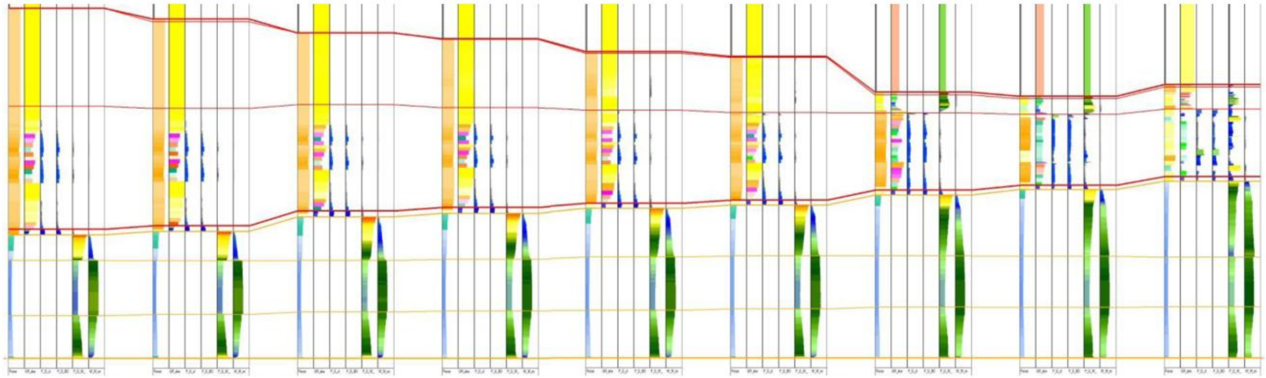
Presenter's notes: Verification and reservoir prediction. Forward models have to be tested against their input data - in this case, it has been achieved by comparing virtual wells from the model with actual well data. Predictions have been blind-tested – in this case, it has been achieved by **NOT** including specific actual wells in the input database (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

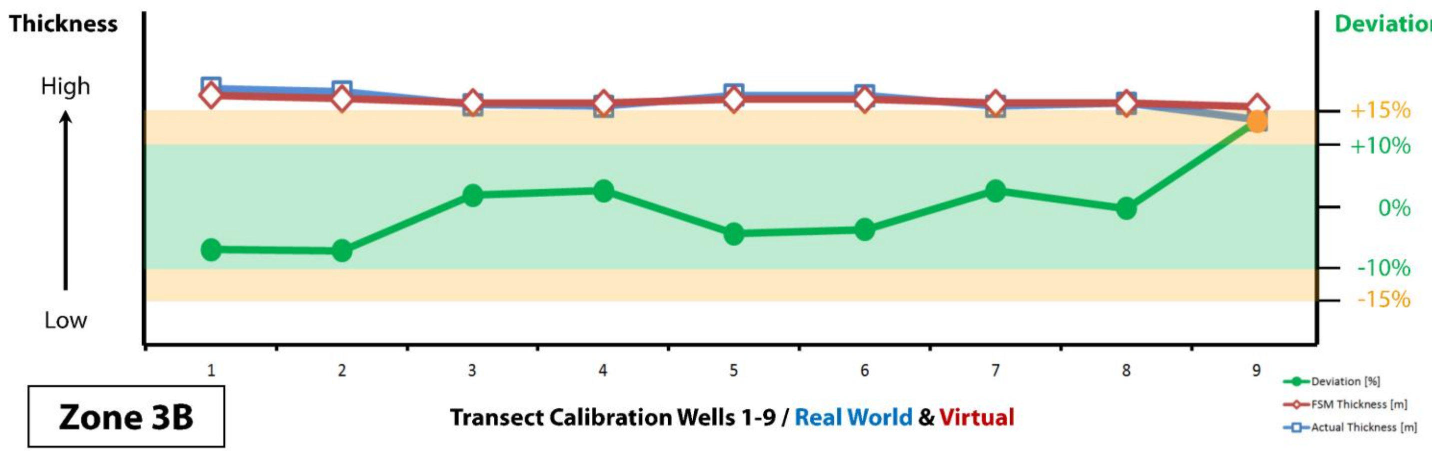
and comparing the prediction form the model with these wells. The upper graph shows a cross section through the forward model in terms of porosity, lithofacies and thickness lines are time lines. The lower graph shows thicknesses (left) and deviations between actual and modeled thickness (right). Blue lines: actual thickness. Red line: modeled thickness. Green line: deviation in percent of actual thickness, up to plus/minus 10% in green, up to plus/minus 15% in orange, higher deviation indicated by red dots. This verification has been performed for each reservoir zone and is a representation of the reliability of the forward stratigraphic model. For reservoir Zone 4: very high reliability

Virtual *VS* Real-World Wells

4. Verification & Reservoir Prediction



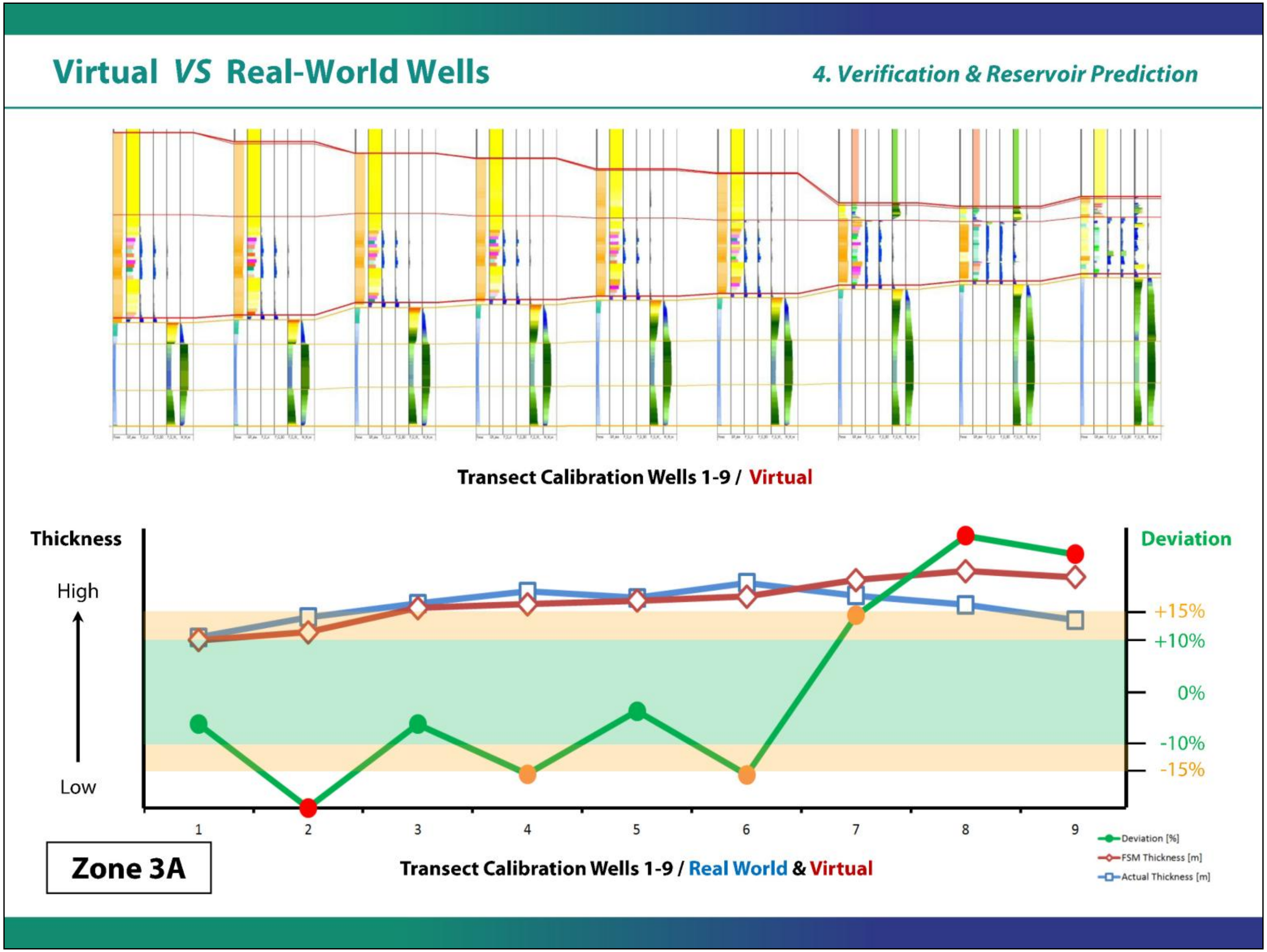
Transect Calibration Wells 1-9 / Virtual



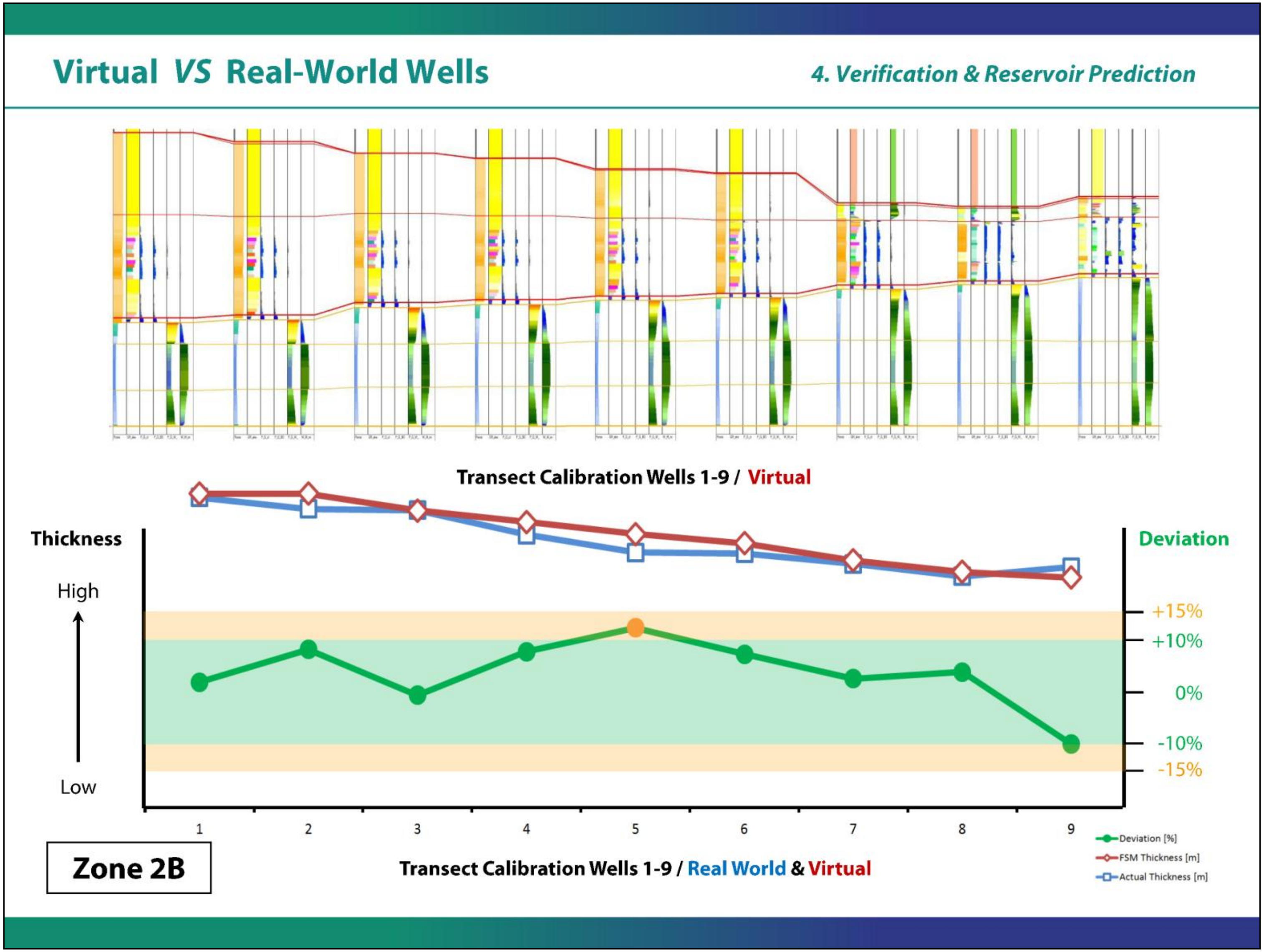
Zone 3B

Transect Calibration Wells 1-9 / Real World & Virtual

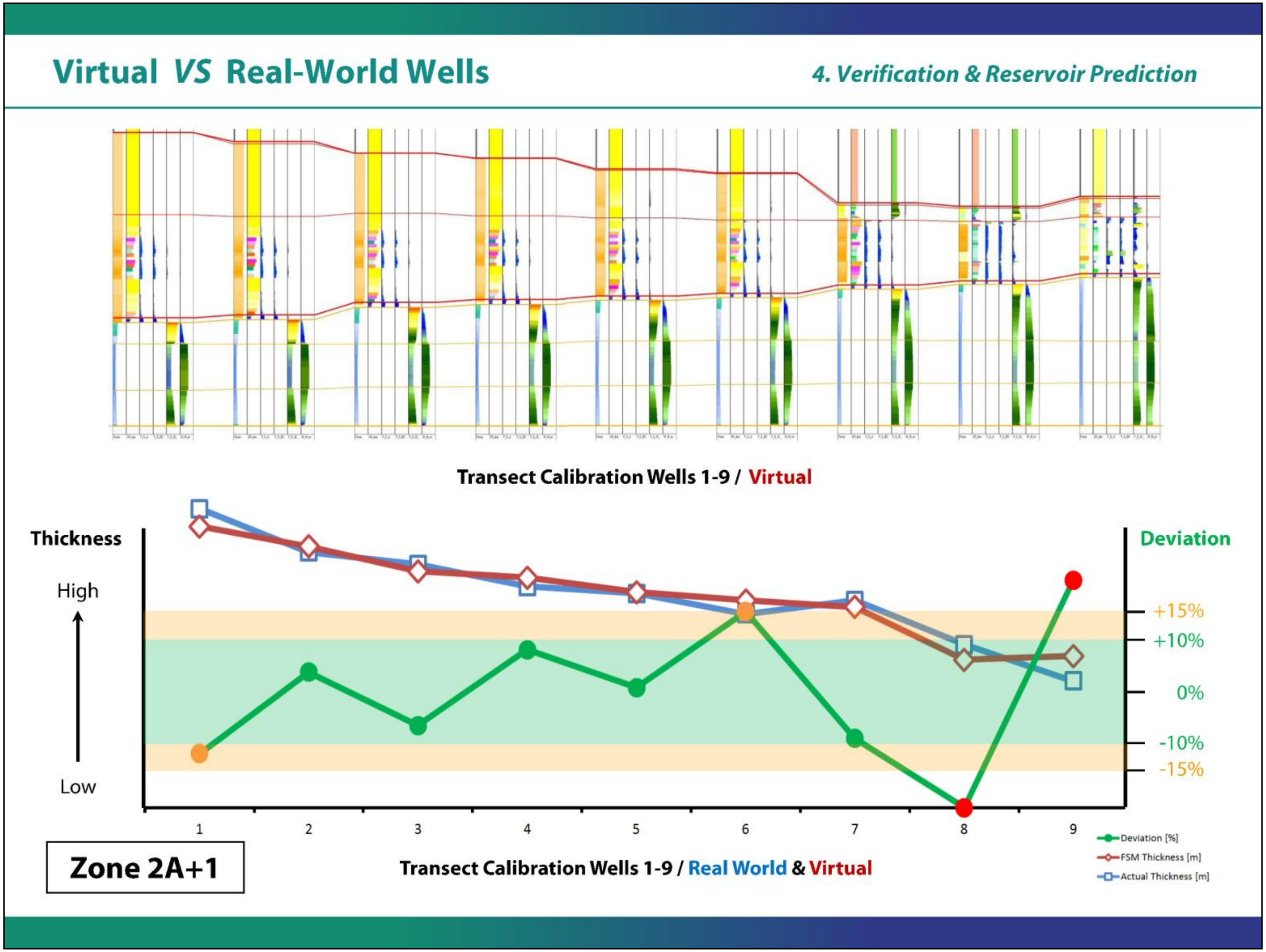
Presenter's notes: For reservoir Zone 3B: very high reliability, slightly decreasing towards the central basin.



Presenter's notes: For reservoir Zone 3A: high reliability, decreasing towards the central basin, possibly related to mass transport.



Presenter's notes: Zone 2B: the lower most important reservoir zone, high reliability across the shoal to basin transition.



Presenter's notes: Zone2 2A+1: the upper most important reservoir zone, high reliability across the upper and middle part of shoal to basin transition, decreasing towards the deeper shelf-interior basin

Blind Test – Virtual VS Actual

4. Verification & Reservoir Prediction

Depositional Environments

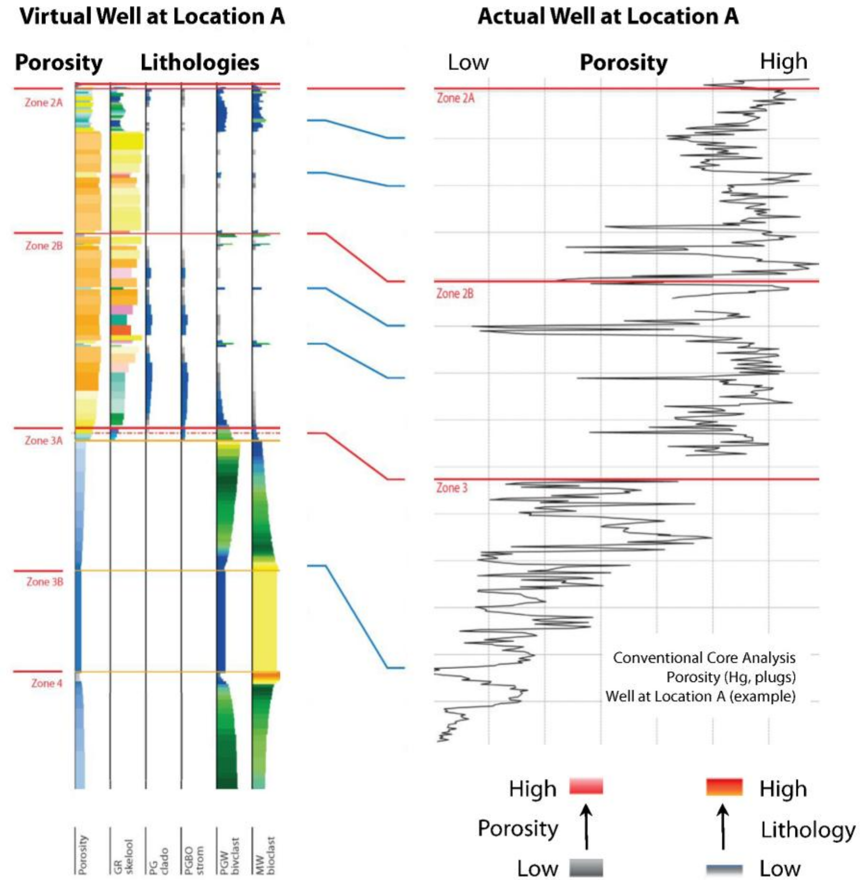
- Trajectories (shoals etc.)
- Facies belts

Sediment Stacking Patterns

- 5-10 m vertical resolution
- ShU & DU-Trends
- most parasequence (sets) represented

Porosity

- 3 pu averaged over 1-3 m reservoir thickness
- Textural porosity only



Presenter's notes: How reliable are predictions at the current point of time. The graph shows a blind test between a virtual well from the model and the corresponding actual well which wqas not included in the database. I cannot include high-resolution numerical values in this presentation, but let us focus on trends: First - in terms of (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

lithofacies and stacking patterns -parasequence sets-. Parasequence sets are adequately predicted in term of thickness, lithofacies and stacking patterns, usually shallowing upward in this case. Second – in terms of porosity, but keep in mind this is textural porosity. In fact porosity is very well predicted up to plus/minus 3 pu in the most important reservoir zones 2A and 2B.

Challenges

1. Integration FSM & RTM

2. Calibration & verification with seismic data

3. Uncertainty & sensitivity modeling

4. Multi-processor & cluster support

Presenter's notes: Conclusions. Which are current challenges in the development of process-based modeling for reservoir quality prediction? (Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

1. Integrate FSM and RTM. This is currently achieved in a predominantly manual, stepwise fashion in industry research units. However, this approach is yet insufficient for E&P units.

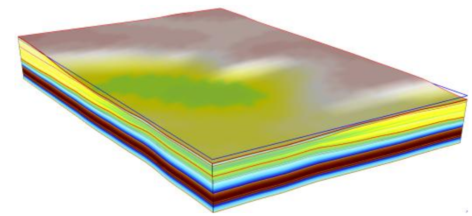
2. Calibrate and verify modeling results with seismic data. This is currently achieved in terms of laps, reflector configurations and geometries. However, no calibration or verification to amplitude and seismic attributes is performed so far.

3. Uncertainty and sensitivity modeling. This is currently performed with a manual or semi-automatic approach. However, more advanced automatic approaches are required for assessing uncertainty and risk in E&P units.

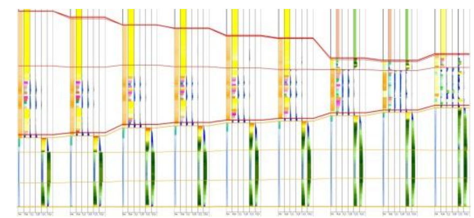
4. Finally, multi-processor and cluster support. This is definitely required in order to compute forward models with high spatial and temporal resolution and comprehensive depositional and diagenetic parameter sets.

Achievements

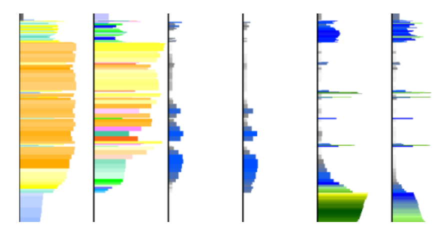
1. GDE prediction for carbonates (& clastics)



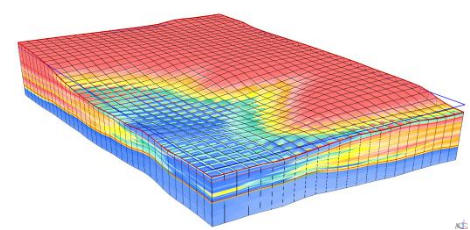
2. Thickness prediction to ≤ 10-15%



3. Stacking patterns at PS to PSS resolution



4. Textural porosity prediction to 3 pu



… Thank you