PS Predicting Reservoir Variation through Simulation of Turbidite Deposition over Restored Paleotopography: A Case Study from the Western Atwater Fold Belt, Gulf of Mexico*

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Abstract

Lower Miocene turbidite reservoirs drilled in the Western Atwater Fold Belt, Gulf of Mexico, exhibit significant variations in gross reservoir thickness, character and quality within individual fields on salt-cored structural highs. Three-dimensional structural restorations based on seismic and well data indicate the presence of significant paleotopography during deposition of these turbidite reservoirs and the observed reservoir variations appear to be systematically related to position on paleotopography. The primary driver of this paleotopography is autochthonous salt diapirism. Understanding the interaction between substrate topography and turbidite sedimentation is critical in attempting to quantitatively predict reservoir variation within these fields.

A new technique used at BHP Billiton Petroleum to help predict these turbidite reservoir variations is to first perform structural restoration to infer paleotopography and then simulate deposition on that paleotopography. The depositional algorithm is based on the work by Waltham (2004) for two-dimensional, depth-averaged gravity currents. One specific geographic area in particular, with three prominent Lower Miocene turbidite reservoirs deposited around a paleostructure estimated to have relief on the order of a few hundred meters, has been modeled. Estimates of the absolute magnitudes of paleotopographic relief have been tested by the degree of similarity of drilled well penetrations and simulation predictions. Reasonable matches to well penetrations were achieved through step-wise modification of the number and character of turbidite flows making up each reservoir.

The critical factors that produce variations in the character of turbidite flow deposits around obstructing topography are relative flow height with respect to paleorelief and flow trajectory relative to paleotopography. Given the uncertainty in multiple parameters (e.g. number of flows, flow width, flow height, flow volume, grain size distribution and parameter variation from flow to flow) it is important that multiple screening scenarios be simulated and multiple well penetrations be matched successfully before having reasonable confidence in additional inter-well predictions. The rapid simulation capability available with depth-averaged simulations enables this testing of multiple scenarios in a reasonable time frame.

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Lower Miocene turbidite reservoirs drilled in the Western Atwater Fold Belt, Gulf of Mexico, exhibit significant variations in gross reservoir thickness, character, and quality within individual fields on salt-cored structural highs. Three-dimensional structural restorations based on seismic and well data indicate the presence of significant paleotopography during deposition of these turbidite reservoirs and the observed reservoir variations appear to be systematically related to position on paleotopography. The primary driver of this paleotopography is autochthonous salt diapirism. Understanding the interaction between substrate topography and turbidite sedimentation is critical in attempting to quantitatively predict reservoir variation within these fields.

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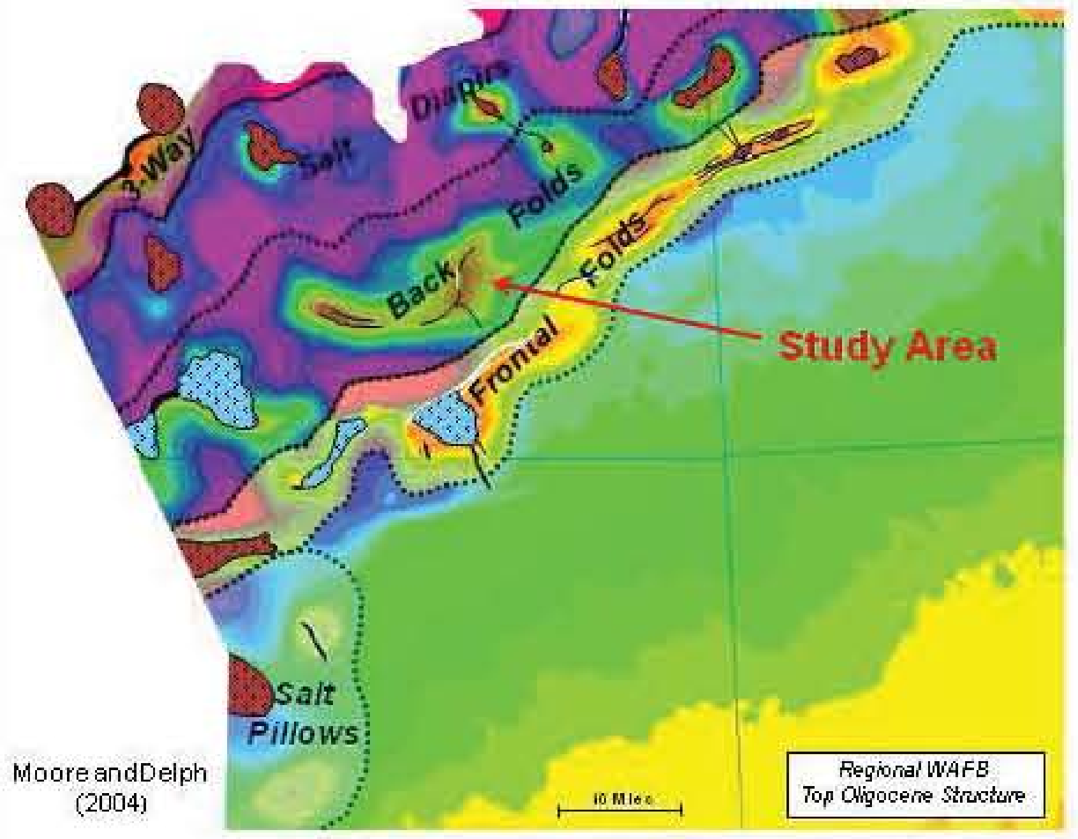
The critical factors that produce variations in the character of turbidite flow deposits around obstructing topography are relative flow height with respect to paleorelief and flow trajectory relative to paleotopography. Given the uncertainty in multiple parameters (e.g. number of flows, flow width, flow height, flow volume, grain size distribution, and parameter variation from flow to flow) it is important that multiple screening scenarios be simulated and multiple well penetrations be matched successfully before having reasonable confidence in additional inter-well predictions. The rapid simulation capability available with depth-averaged simulations enables this testing of multiple scenarios in a reasonable time frame.

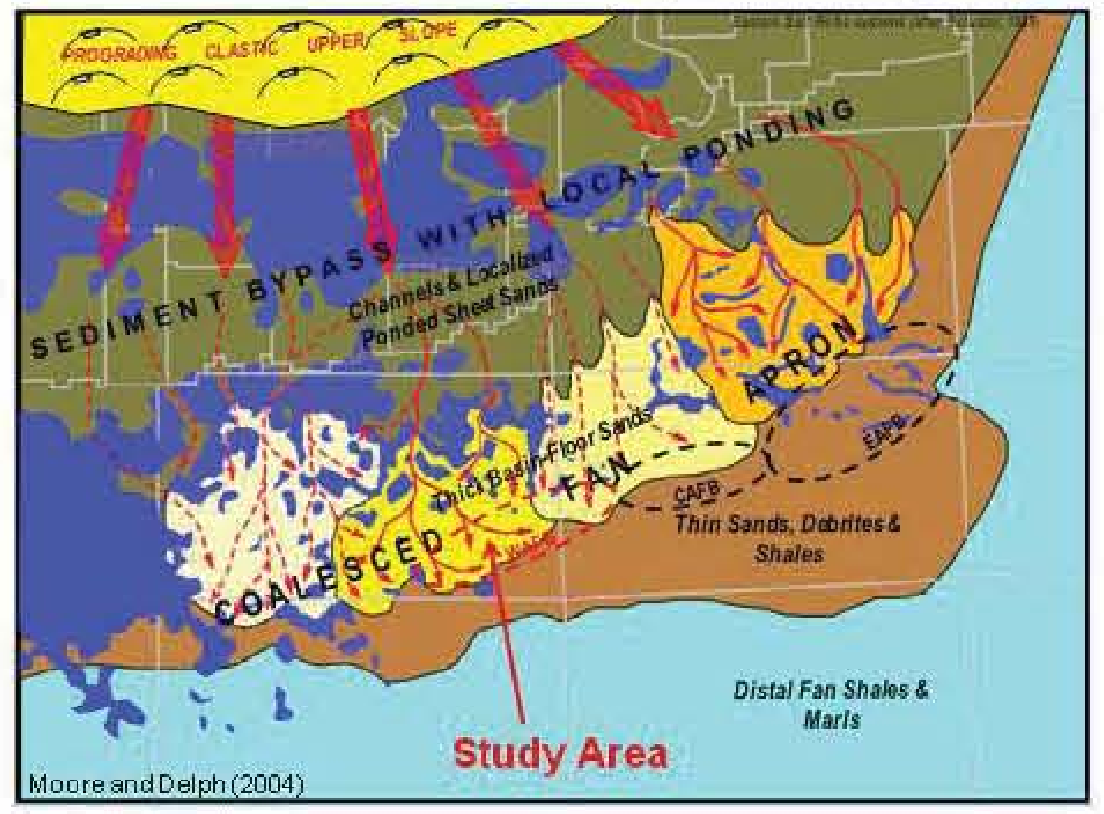
Regional Setting

Western Atwater Fold Belt Structural Provinces



Moore and Delph (2004)

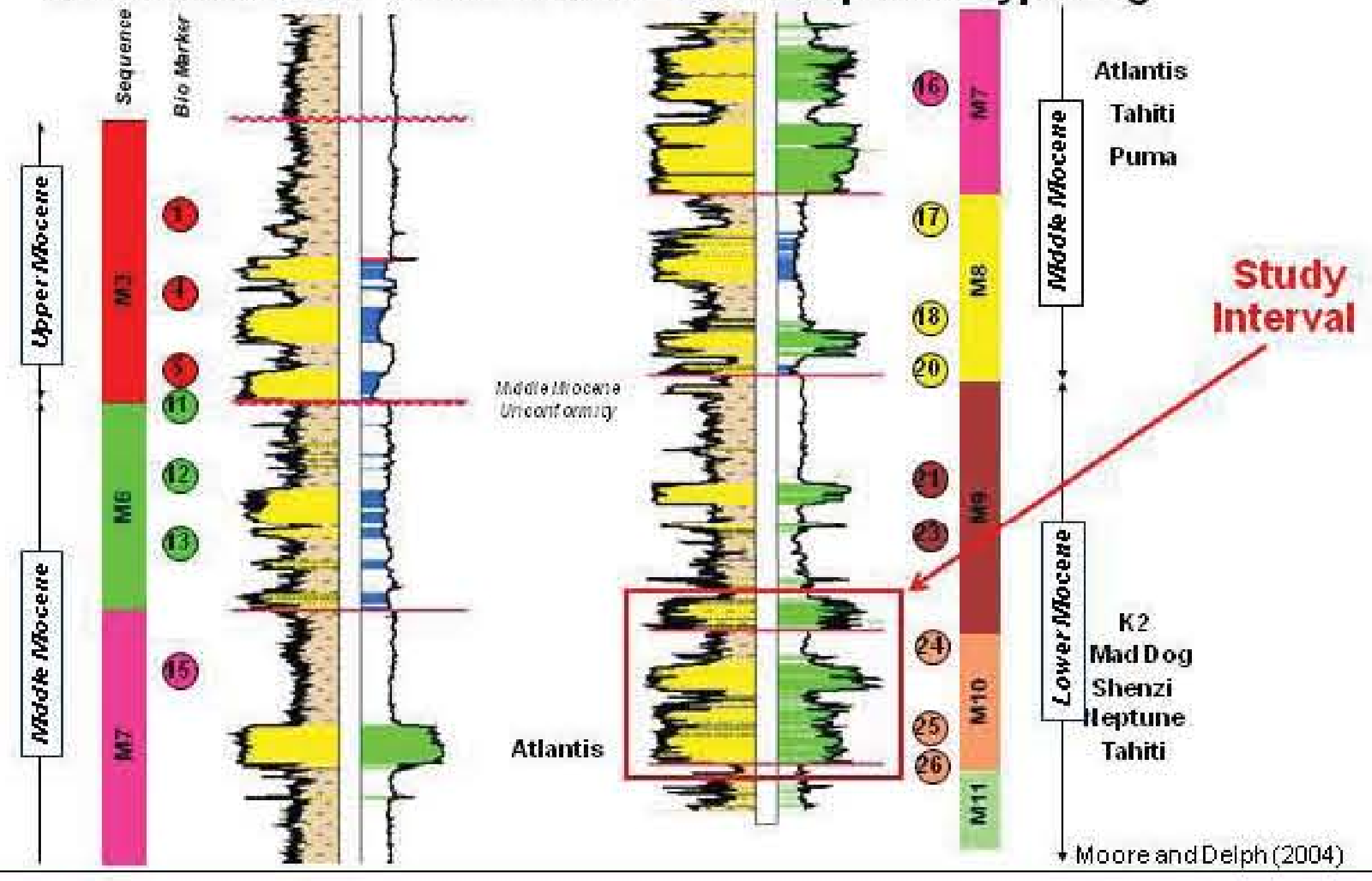
Lower and Middle Miocene Depositional Systems



Moore and Delph (2004)

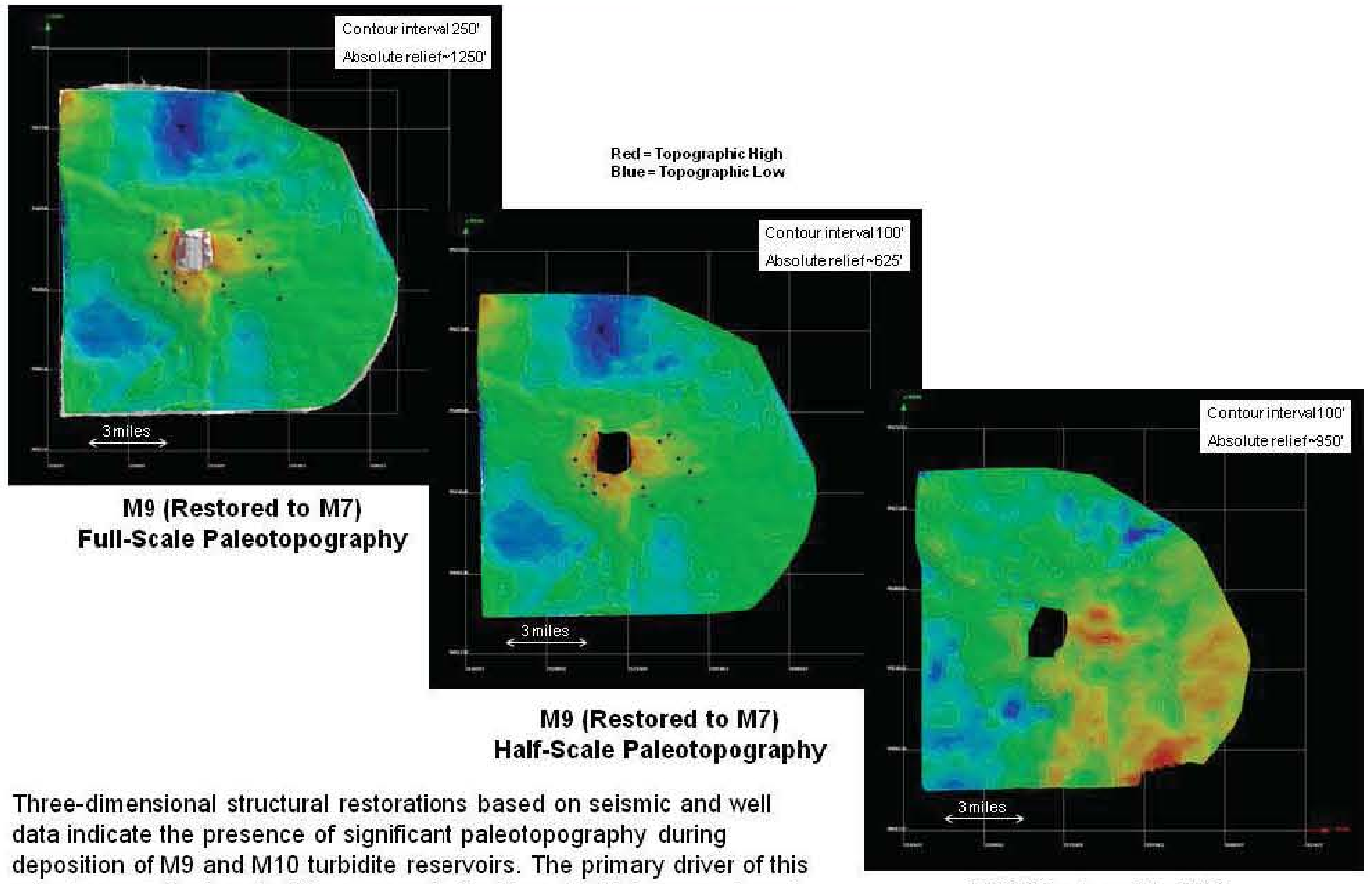
Western Atwater Fold Belt Miocene Composite Type Log

The study area is within the "Back Folds" portion of the Western Atwater Fold Belt (WAFB), Gulf of Mexico. The stratigraphic interval of interest is the Lower Miocene (M9-M10), containing multiple turbidite reservoirs.



Moore and Delph (2004)

Scenarios of Restored Paleotopography



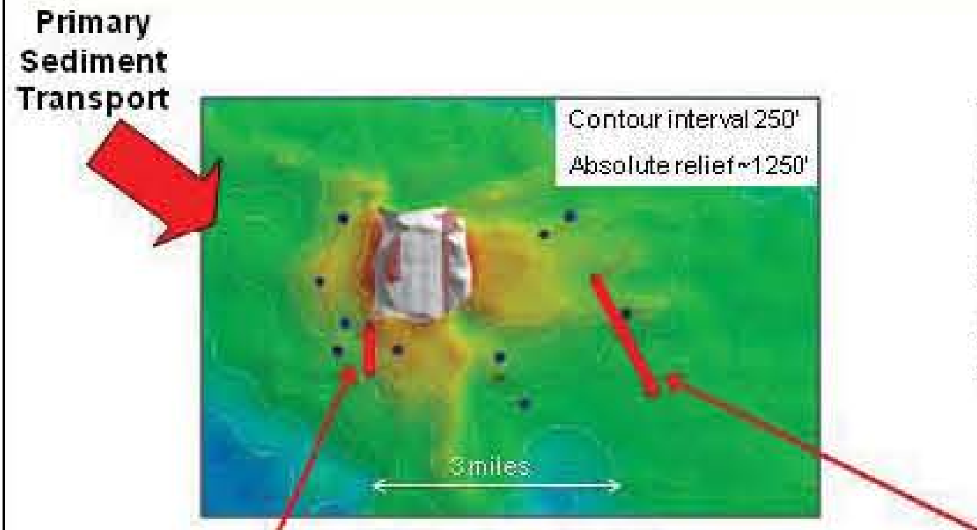
M9 (Restored to M7)
Full-Scale Paleotopography

M9 (Restored to M7)
Half-Scale Paleotopography

M10 (Restored to M9)
Paleotopography

Three-dimensional structural restorations based on seismic and well data indicate the presence of significant paleotopography during deposition of M9 and M10 turbidite reservoirs. The primary driver of this paleotopography is autochthonous salt diapirism. Multiple scenarios of topography have been generated, based on density of mapped sequence boundaries (M7, M9, M10). Each of these paleotopographic scenarios has been tested via simulation of reservoir deposition.

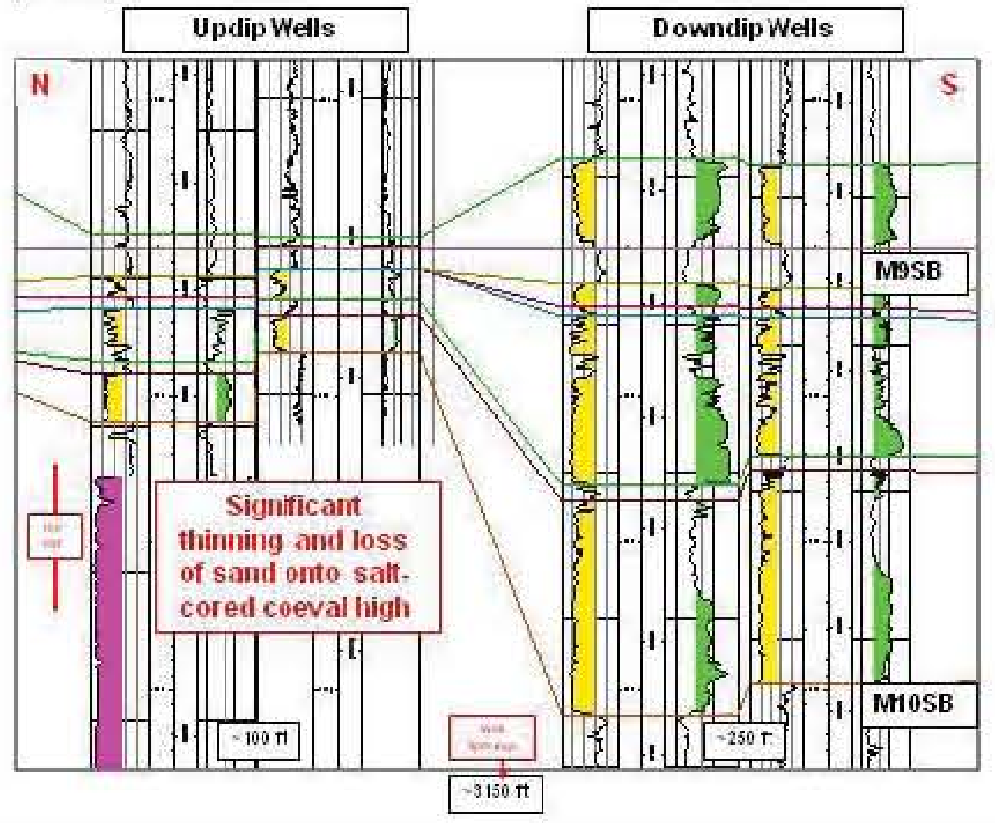
Reservoir Variation Related to Paleotopography



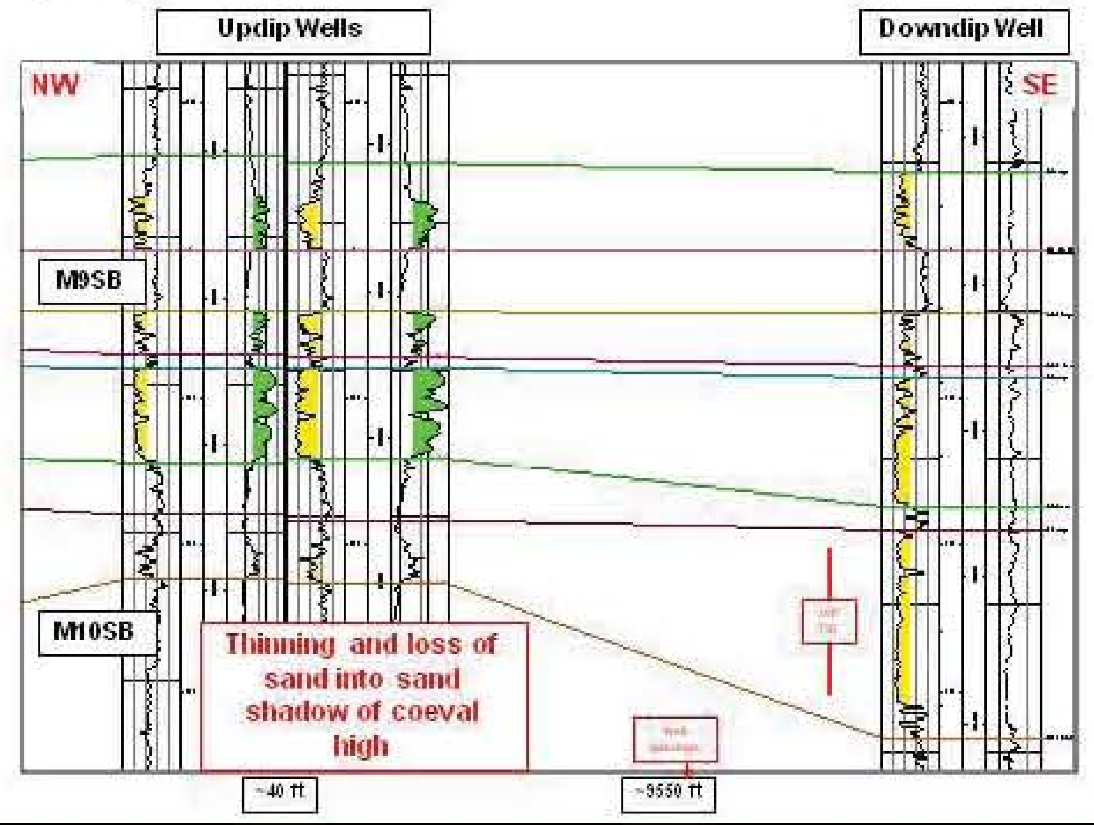
M9 (Restored to M7)
Full-Scale Paleotopography

These turbidite reservoirs often exhibit significant variations in gross reservoir thickness, character, and quality on these salt-cored structural highs. The structural restorations indicate the presence of significant paleotopography during deposition of these turbidite reservoirs and the observed reservoir variations appear to be systematically related to position on paleotopography.

Depositional Strike Stratigraphic Cross Section (TST)

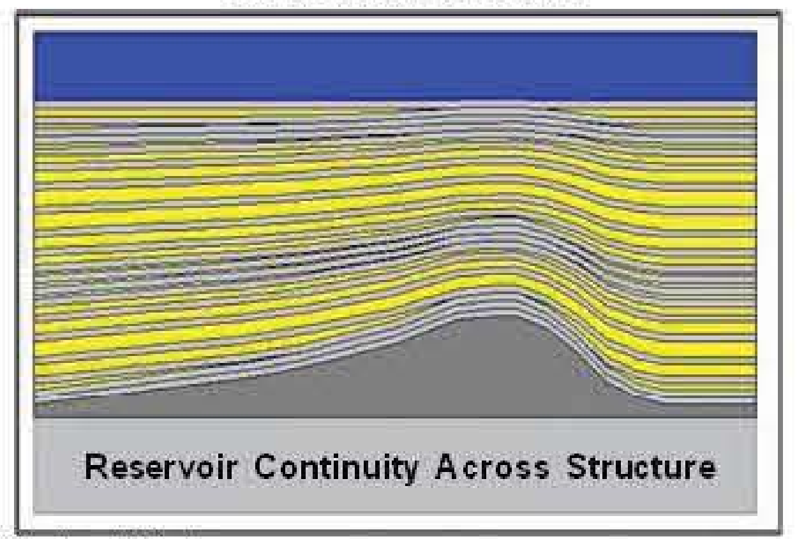


Depositional Strike Stratigraphic Cross Section (TST)



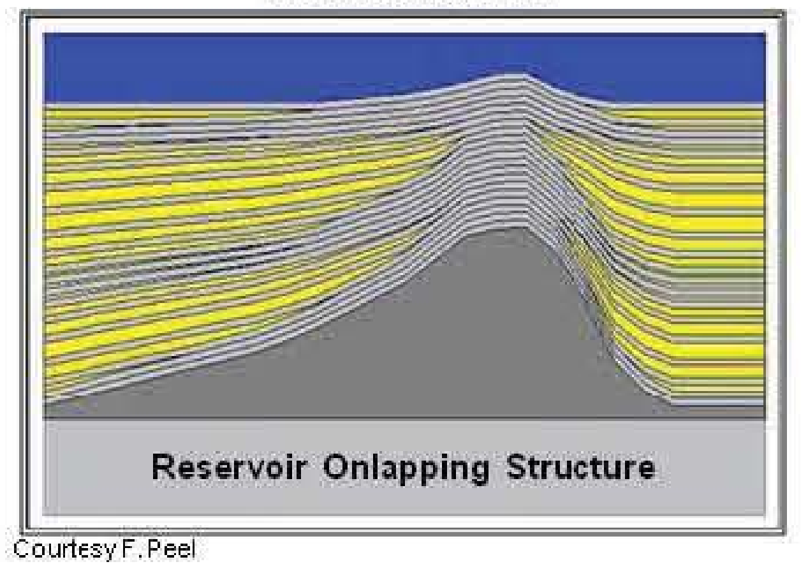
Interaction of Structure and Sedimentation

Sedimentation Outpacing Structural Growth



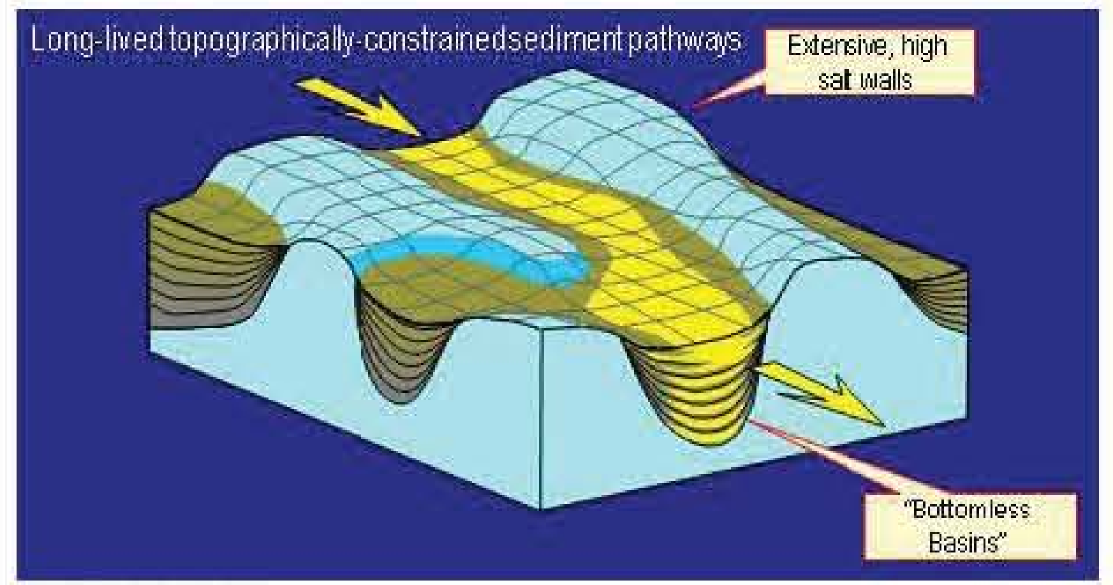
Courtesy F. Peel

Structural Growth Outpacing Sedimentation

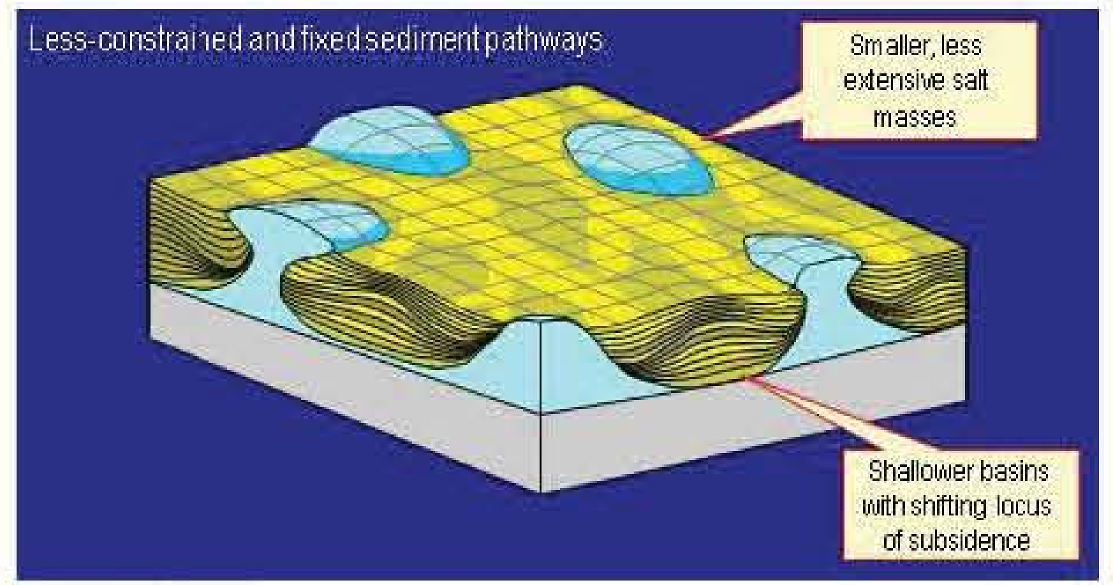


Courtesy F. Peel

Understanding the interaction between substrate topography and turbidite sedimentation is critical in attempting to quantitatively predict reservoir presence and variation both at the field scale (above) and regionally (below).



Apps and Peel (2004)



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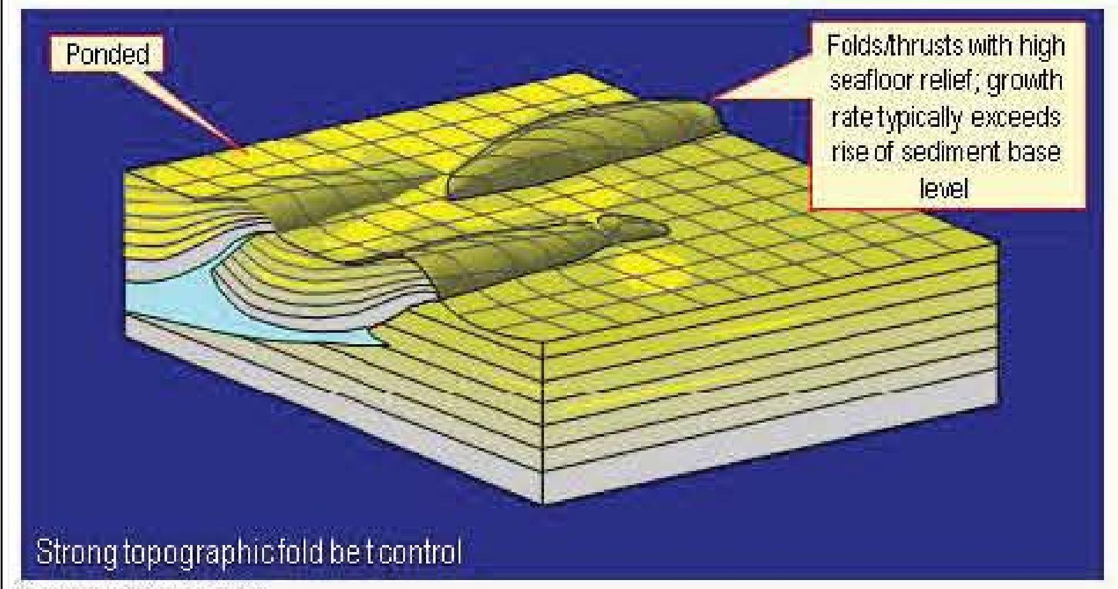

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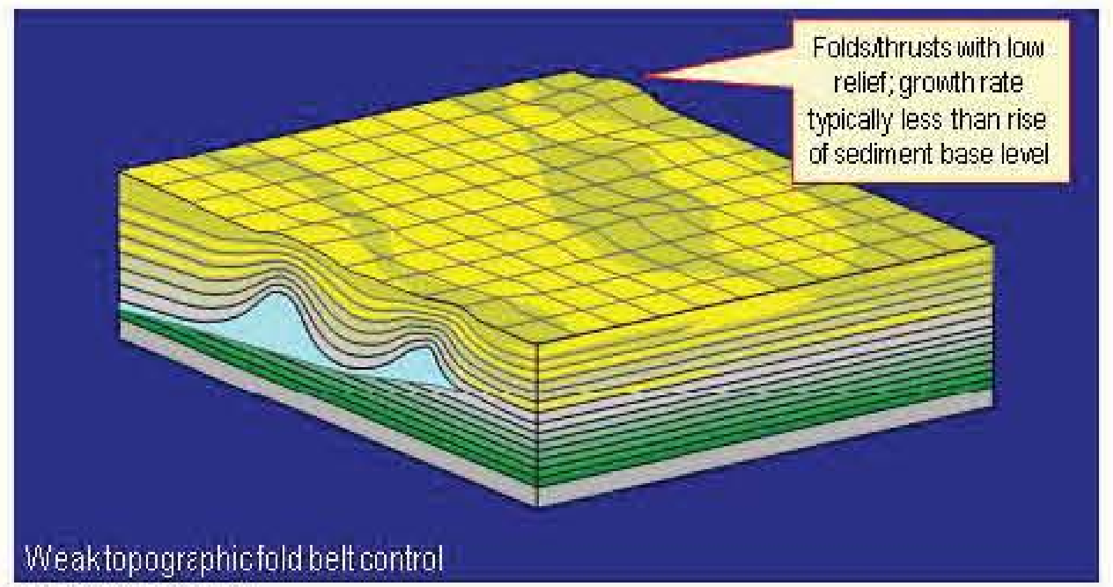
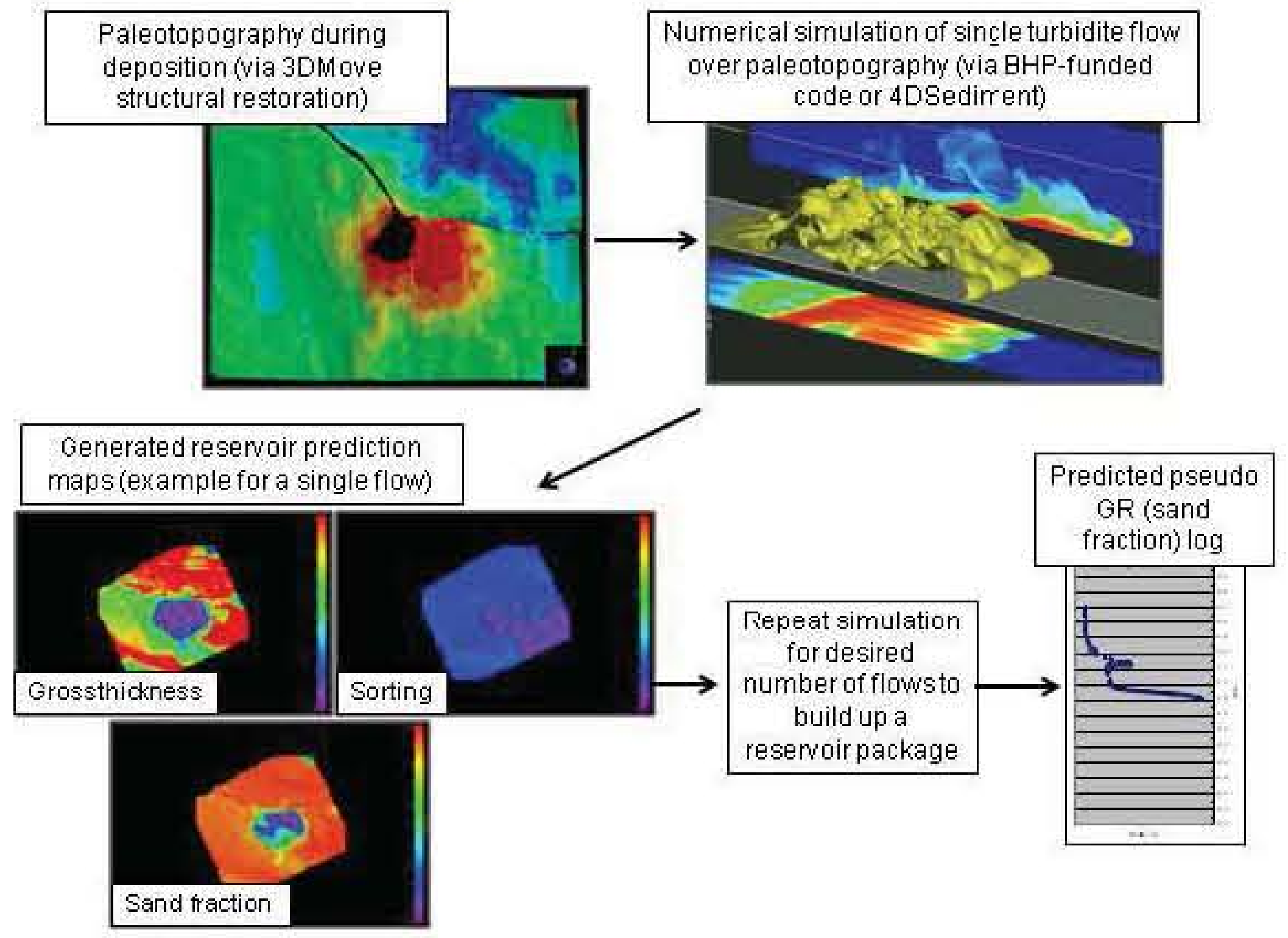


Apps and Peel (2004)

Simulation of Turbidite Reservoir Deposition

A new technique used to help predict turbidite reservoir variation around paleotopography is to first perform structural restoration to infer paleotopography, and then simulate deposition over that paleotopography. The depositional algorithm used here is based on work by Waltham (2004) for two-dimensional, depth-averaged gravity currents. These single flows are then repeated the desired number of times over updated paleotopography to build up a reservoir package. This simulated reservoir can then be intersected by an existing or planned well trajectory to generate a predicted sand fraction (pseudo GR) log.



Paleotopography during deposition (via 3DMove structural restoration)

Numerical simulation of single turbidite flow over paleotopography (via BHP-funded code or 4DSediment)

Generated reservoir prediction maps (example for a single flow)

Repeat simulation for desired number of flows to build up a reservoir package

Predicted pseudo GR (sand fraction) log

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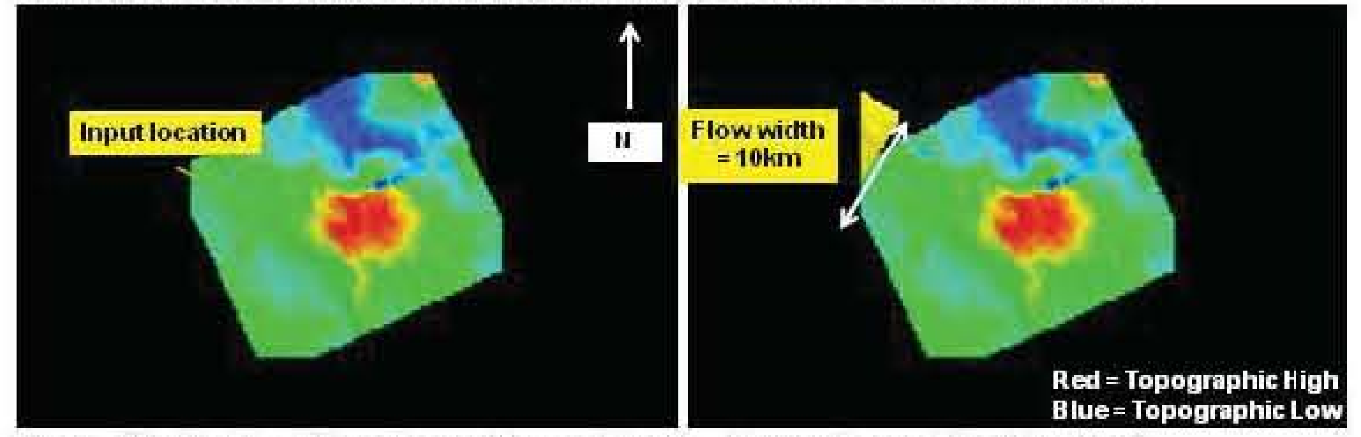
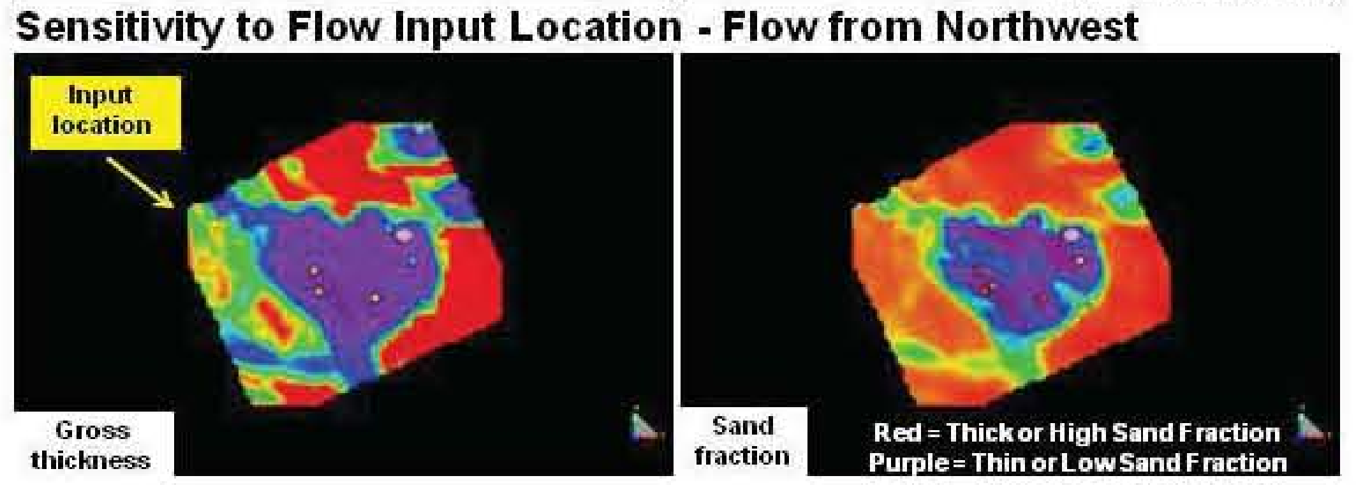
Sensitivity of Turbidite Deposits to Flow Parameters

Initial Flow Definition: Flow From Northwest, 10km Width



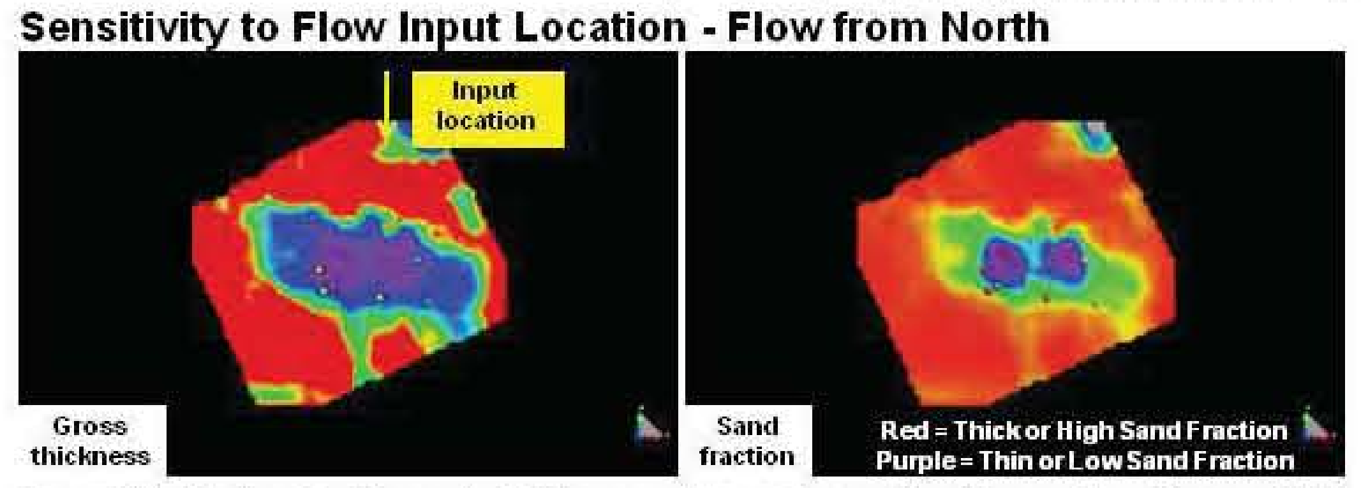
Three primary flow parameters are input location, flow direction, and flow width. All three parameters were varied to examine the impact on the resulting flow deposit. All runs are single flow deposits (30 km^3 sediment volume) except where otherwise noted. For reference the Grand Banks historical event is estimated at 150-180 km^3.

Sensitivity to Flow Input Location - Flow from Northwest



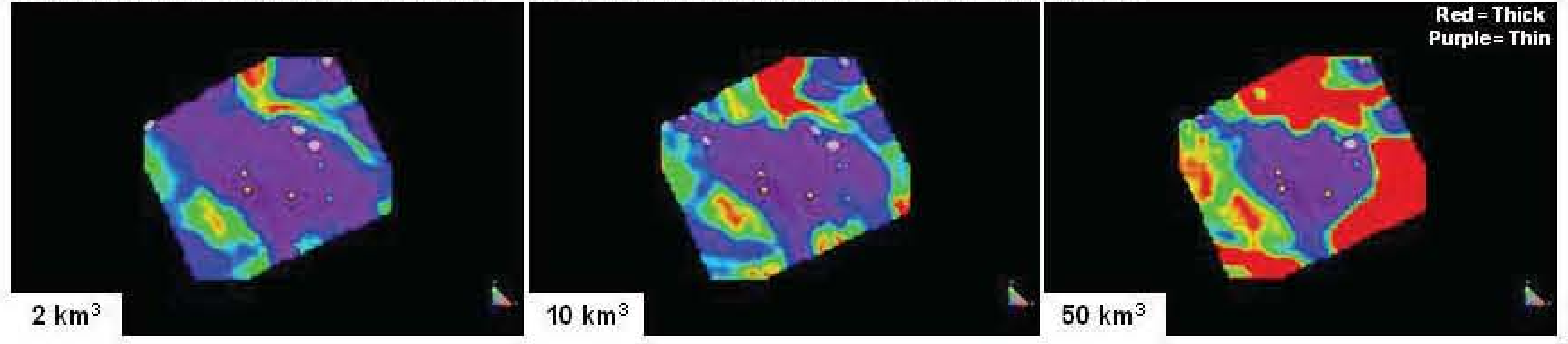
Flow from the northwest toward the southeast results in significant deposition around the paleohigh, with only traces of deposition in subtle relief on the high.

Sensitivity to Flow Input Location - Flow from North

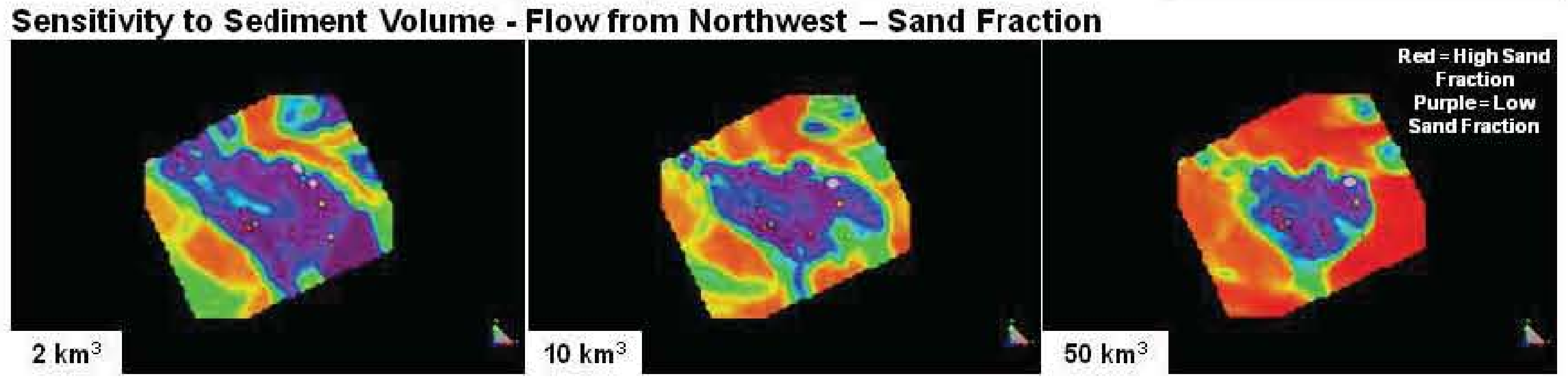


Flow from the north toward the south results in significantly thicker deposition around the paleohigh and on the flanks (due to less sediment being bypassed). The paleohigh acts as a more efficient backstop in this case.

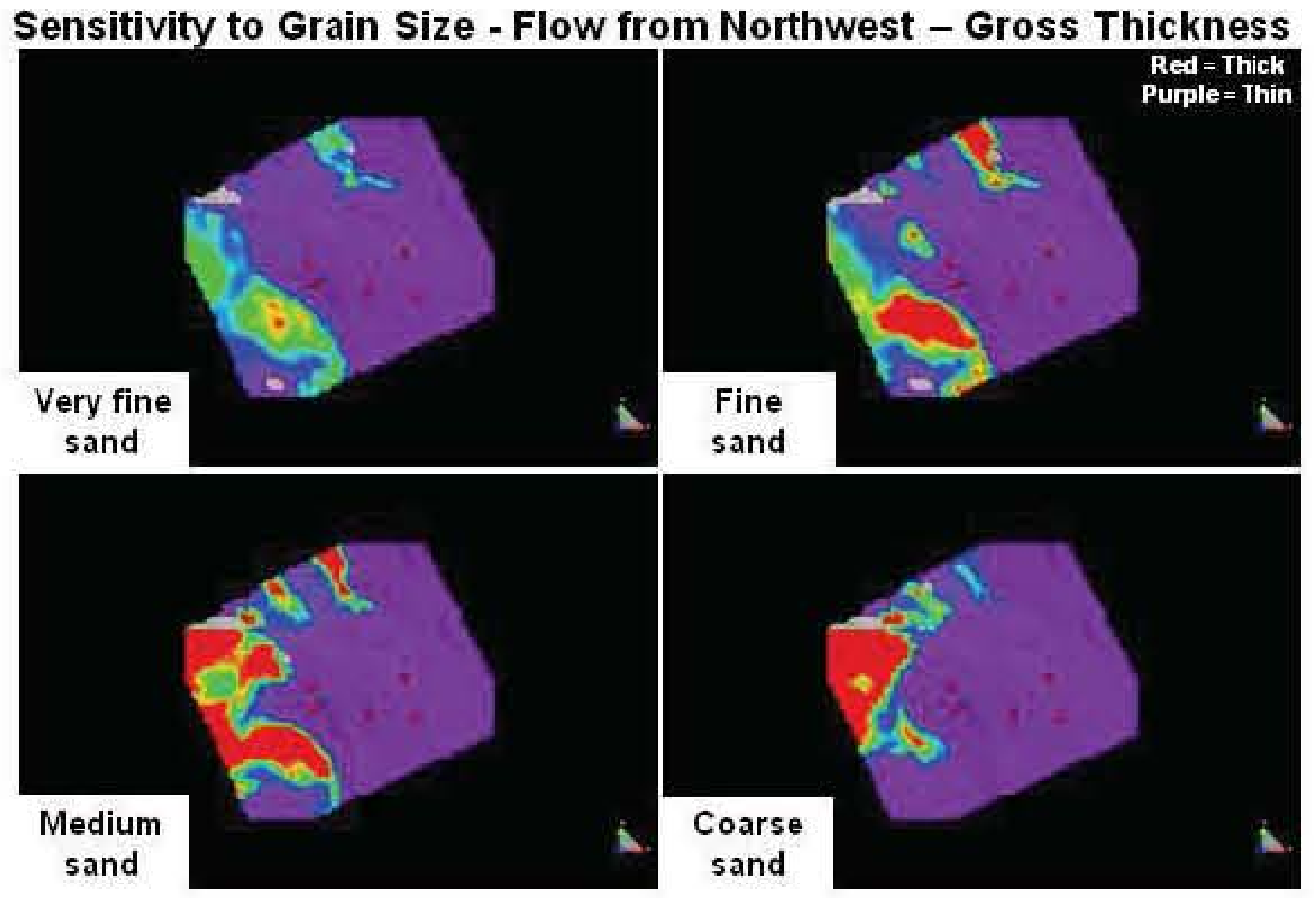
Sensitivity to Sediment Volume - Flow from Northwest – Gross Thickness



Sensitivity to Sediment Volume - Flow from Northwest – Sand Fraction



Sensitivity to Grain Size - Flow from Northwest – Gross Thickness

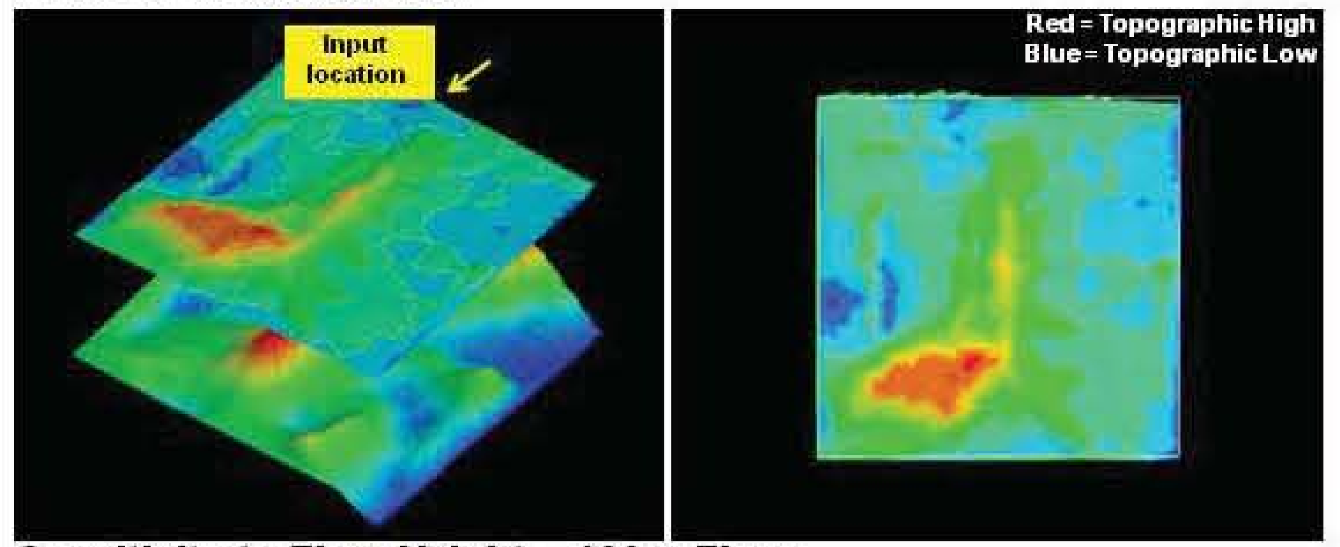


Larger sediment volume flows fill up the accommodation space around the paleohigh faster, but there is still significant bypass. Typical percentages of sediment bypassed in these cases, with flow from the northwest and towards the southeast is 90-95%.

Varying the average grain size results in coarse and medium grained sand being deposited closer to the source due to more rapid settling. More of the very fine sand grained flows bypass the area

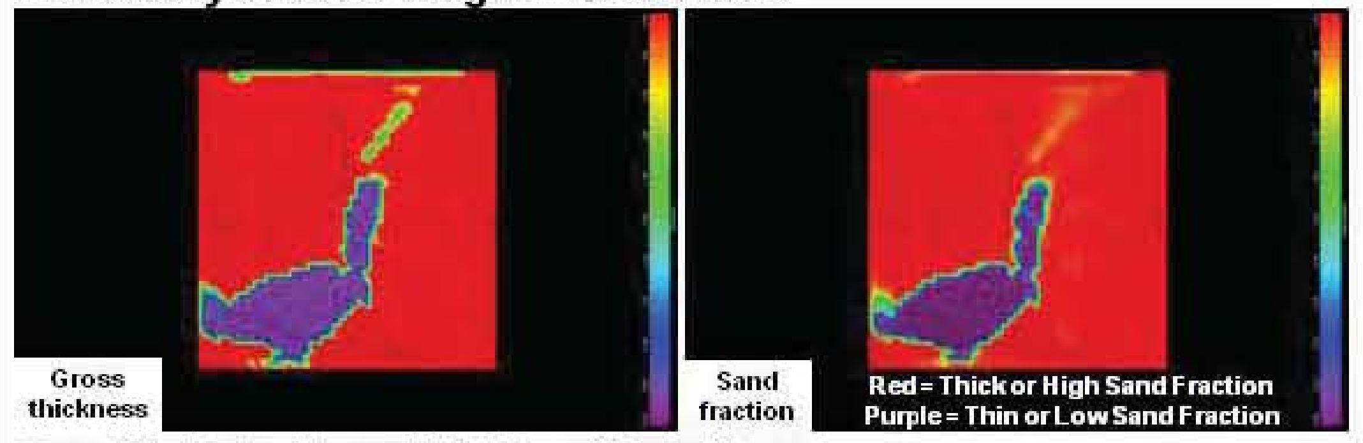
Flow Height Relative to Topographic Relief

Field Scale Restoration



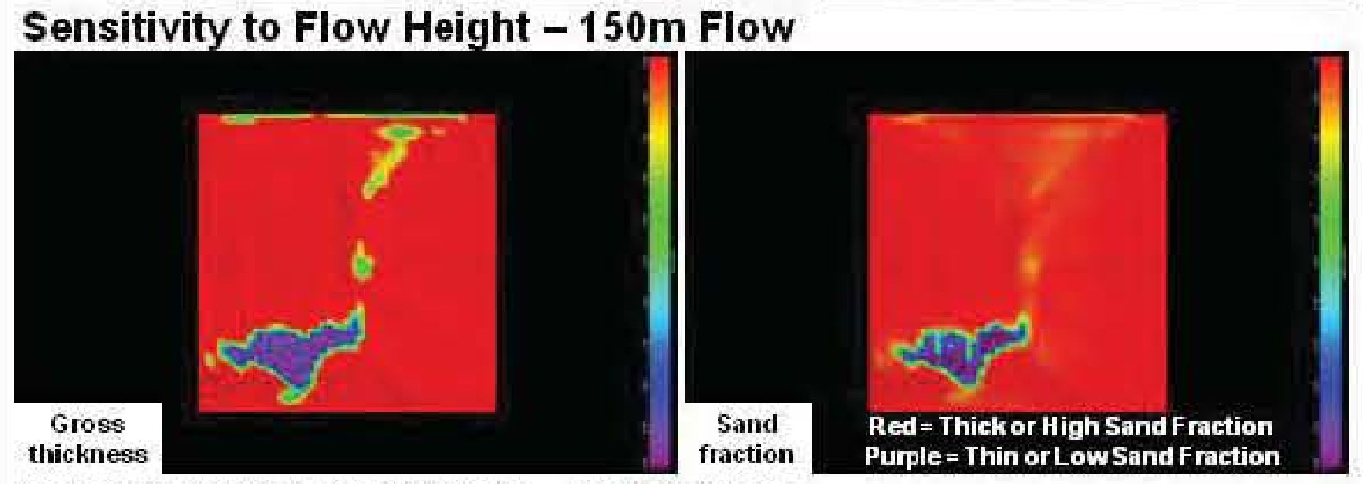
Flow height relative to topographic relief, and the flow trajectory relative to paleotopographic shape are two very important drivers of the character of resulting deposits. Note the difference in size, relief, and breadth of the central ridge compared to high to the lower left. Each of these runs are single flow deposits with 30 km^3 sediment volume, with varying flow heights.

Sensitivity to Flow Height – 100m Flow



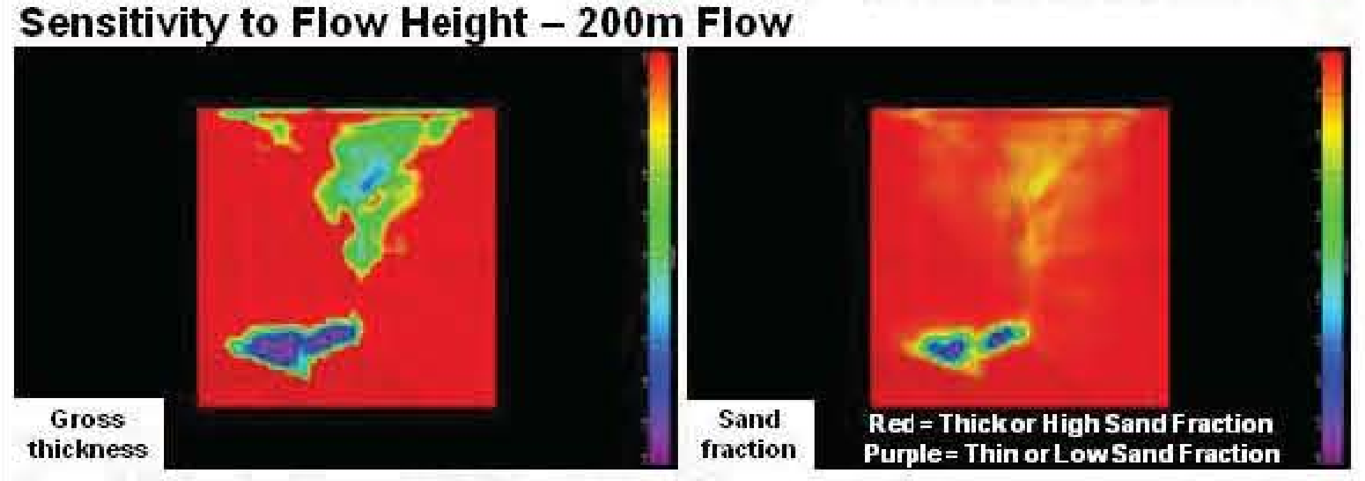
A 100 meter flow height results in much of both the central ridge and the lower left high not being covered by sediment.

Sensitivity to Flow Height – 150m Flow



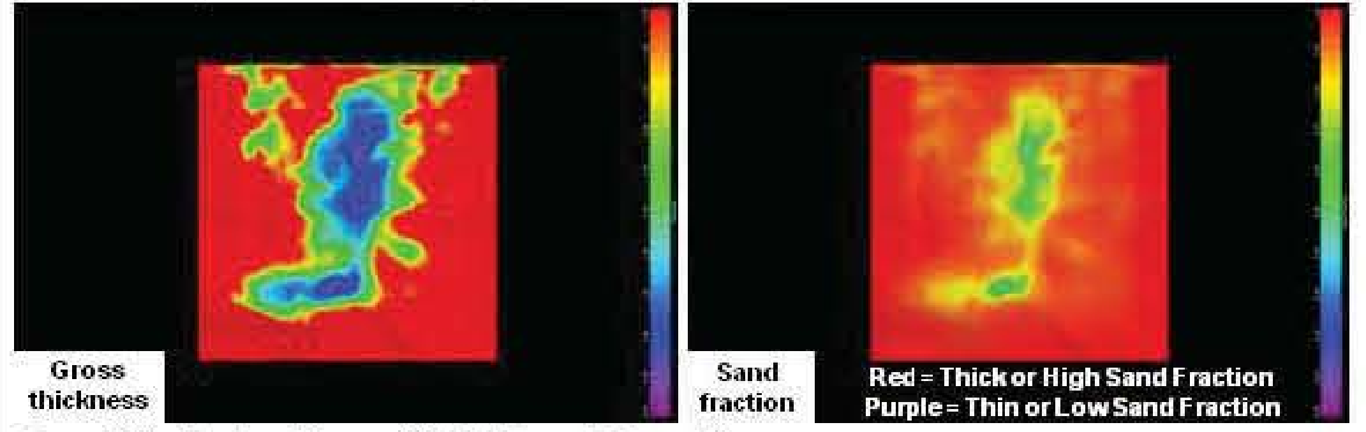
Increasing the flow height by only 50 meters results in almost full coverage of the central ridge and only partial coverage of the lower left high.

Sensitivity to Flow Height – 200m Flow

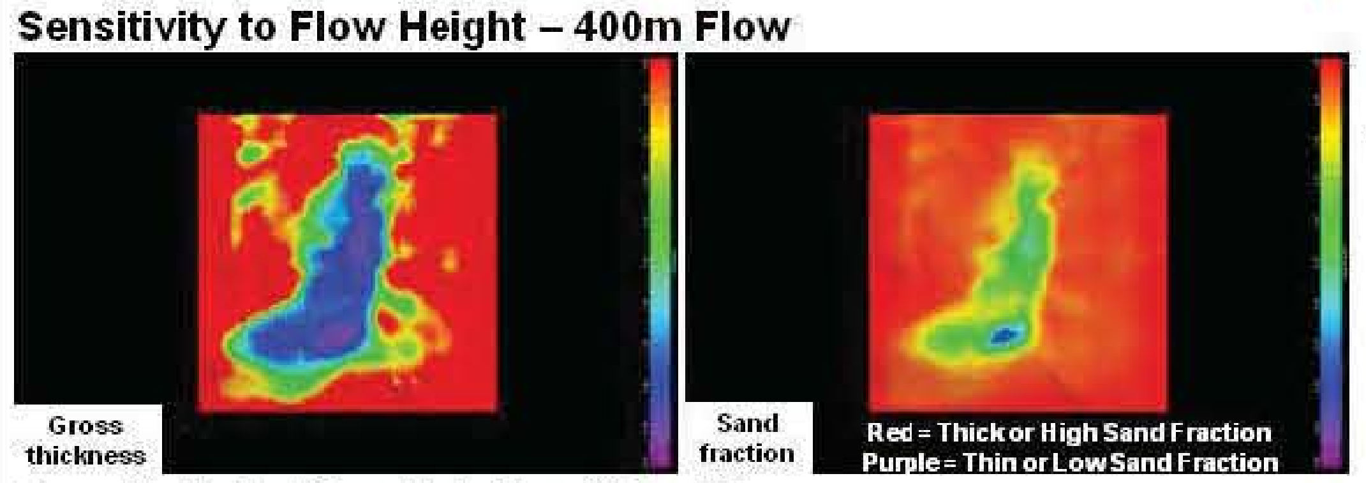


Increasing the flow height further results in less coverage again of both highs.

Sensitivity to Flow Height – 300m Flow

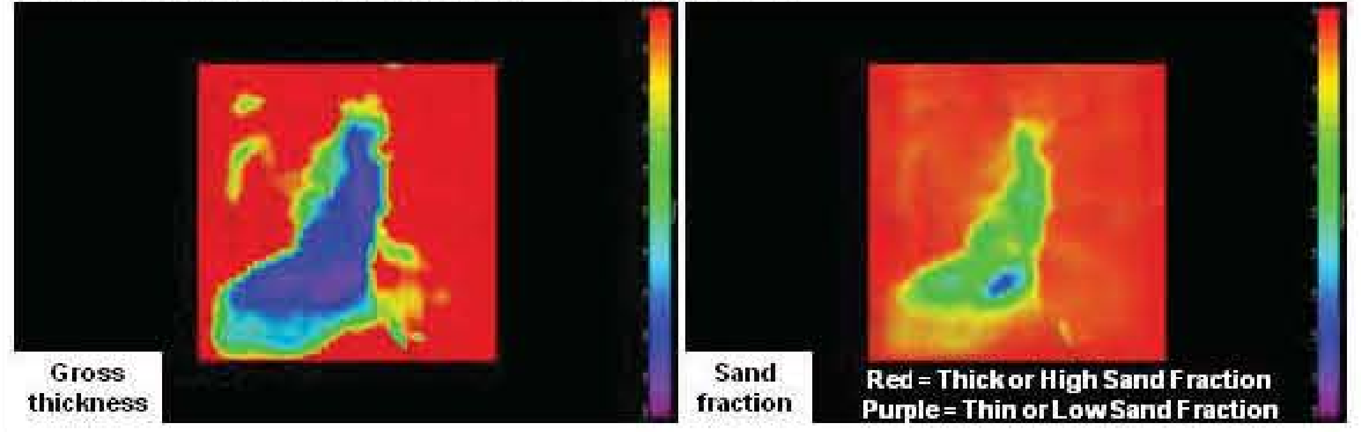


Sensitivity to Flow Height – 400m Flow



There is a very narrow range of flow heights in this case, with a single flow, which results in full coverage of the central high. It is character like this that helps one "tune in" flow parameters that are most consistent with other data and interpretations such as well control and reservoir correlation

Sensitivity to Flow Height – 500m Flow

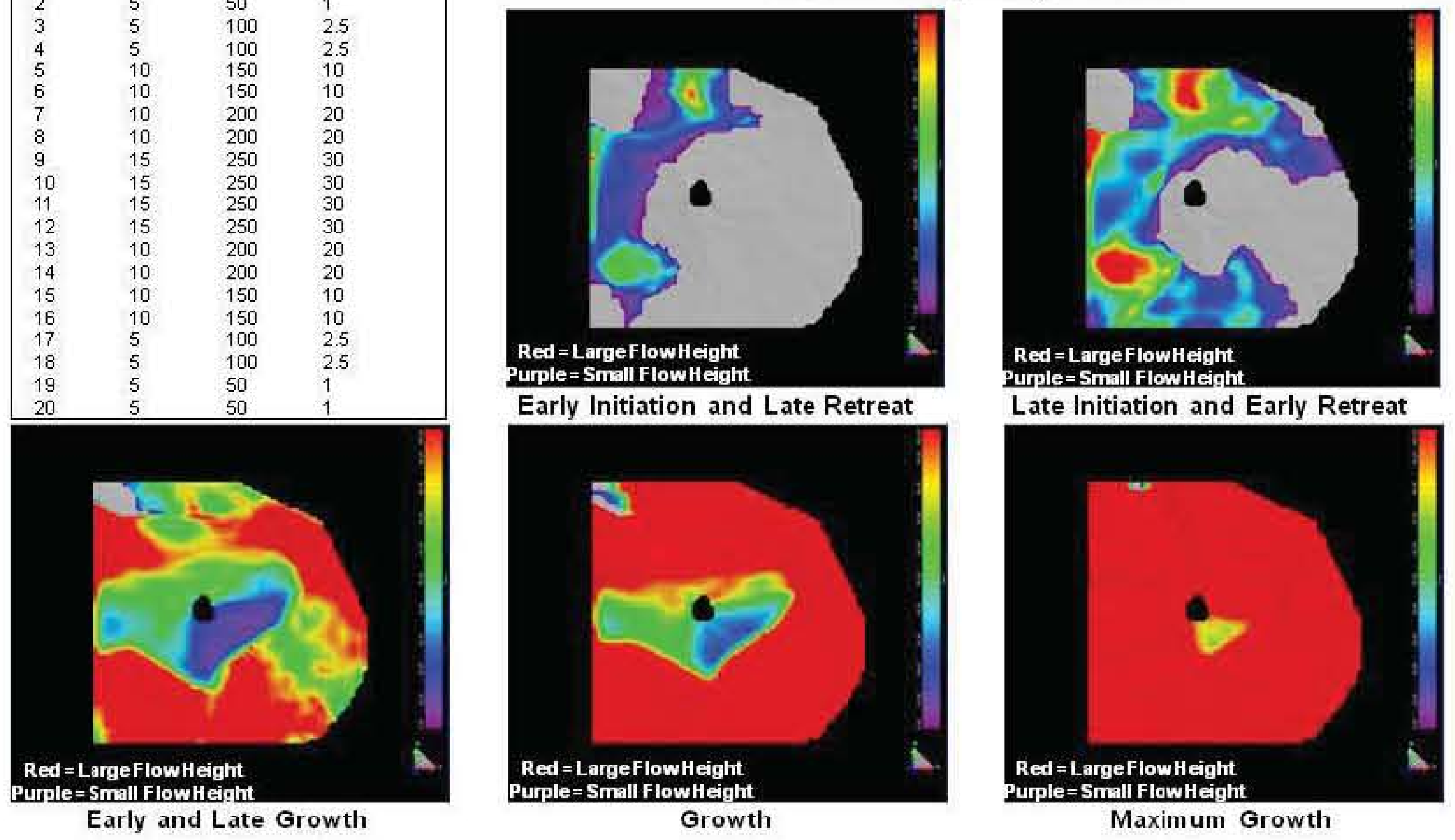


Cyclic Variation in Turbidite Flow Event Parameters

Turbidite systems go through cyclical energy variations over time. One model that summarizes this behavior, allows for comparison between systems, and allows prediction within systems is the AIGR model (Gardner, et al., 2008). AIGR refers to the four phases of deep-water stratigraphic system evolution: adjustment, initiation, growth, and retreat. This model has been applied to the turbidite flow simulations here, where many of the flow parameters are varied in a cyclic fashion to aid in the creation of realistic looking turbidite reservoirs made up of deposits from multiple flows. In this case note that initiation and retreat flows do not breach the paleohigh, whereas growth phase flows do.

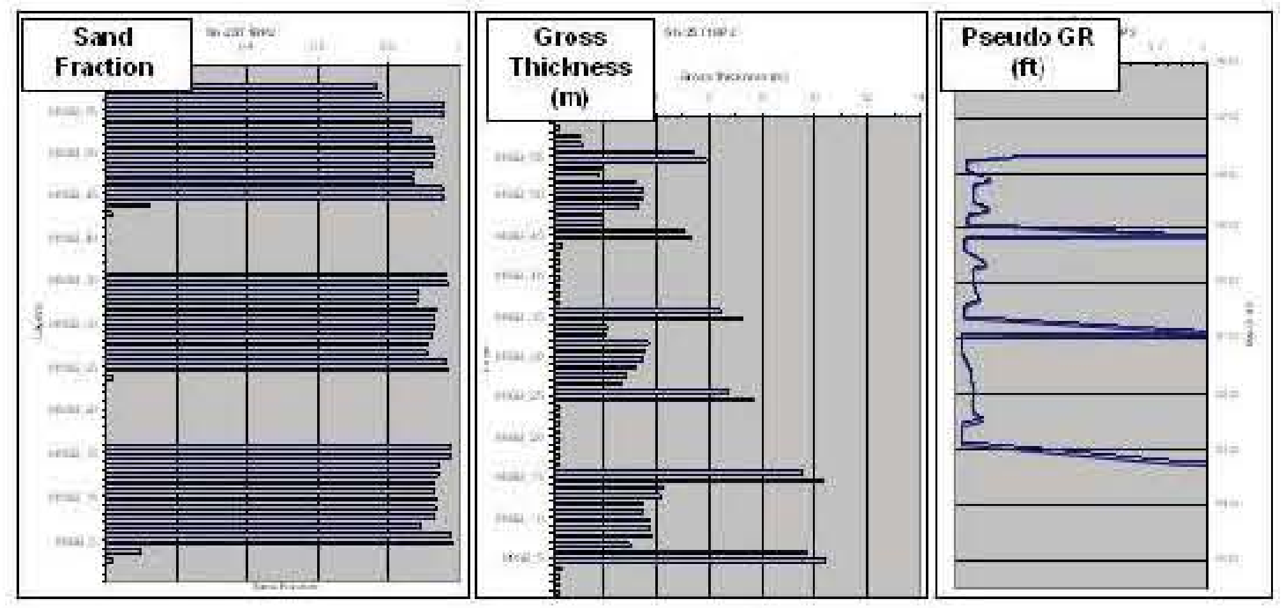
Flow	Width (km)	Height (m)	Volume (km^3)
1	5	50	1
2	5	50	1
3	5	100	2.5
4	5	100	2.5
5	10	150	10
6	10	150	10
7	10	200	20
8	10	200	20
9	15	250	30
10	15	250	30
11	15	250	30
12	15	250	30
13	10	200	20
14	10	200	20
15	10	150	10
16	10	150	10
17	5	100	2.5
18	5	100	2.5
19	5	50	1
20	5	50	1

Mid-Flow Flow Height Images From Successively Larger Flows

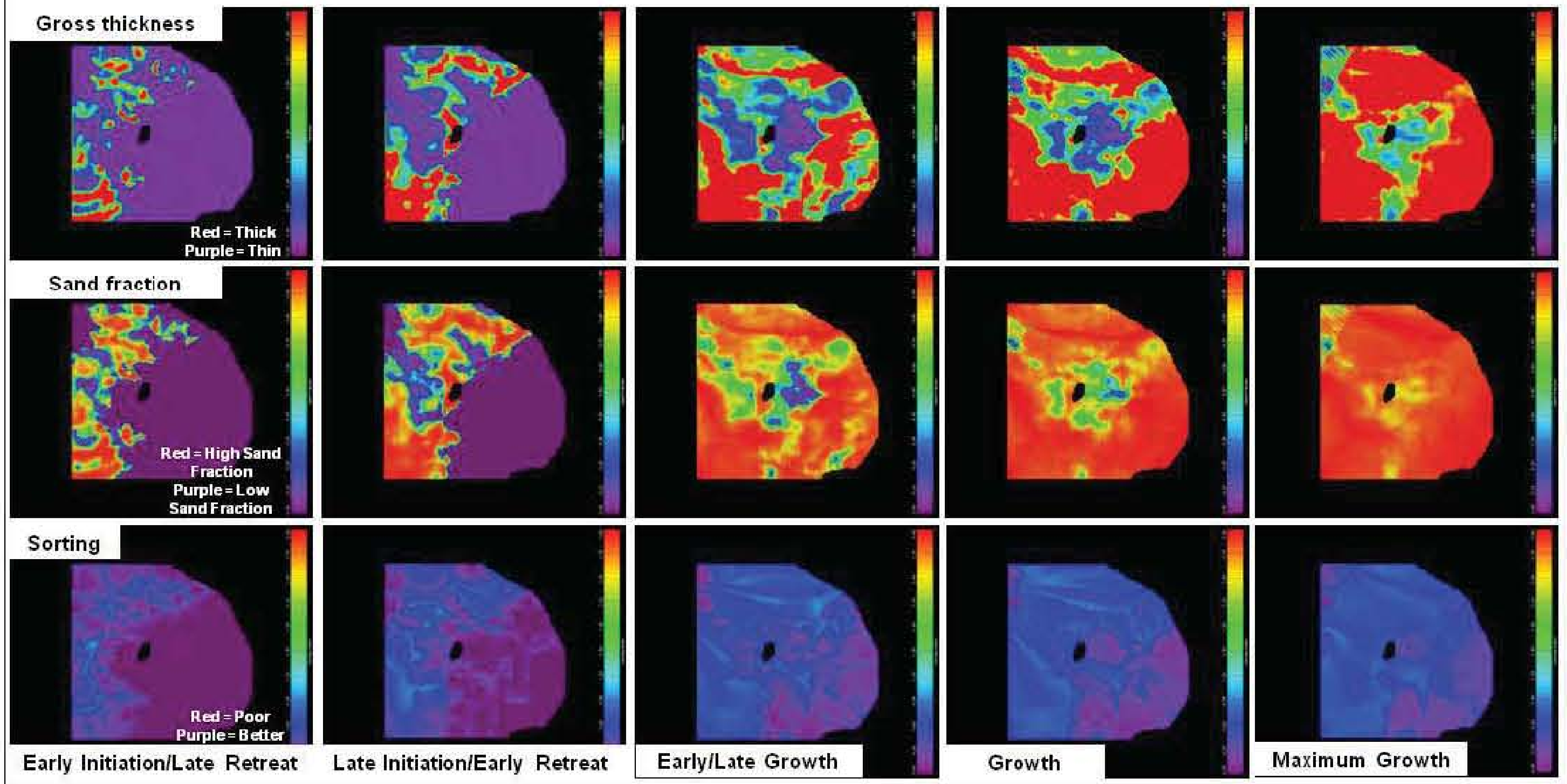


The sand fraction, gross thickness, and pseudo GR graphs to the right show an example of the deposits resulting from three such cycles. Note that growth phase flows do not always create the thickest deposits at a given location as it is the large growth phase flows that also bypass the most sediment.

An Example Result at One Location of Three Cycles of Deposition



The matrix of images below shows example gross thickness, sand fraction, and sorting maps of the resulting deposits of the initiation, growth, and retreat flows



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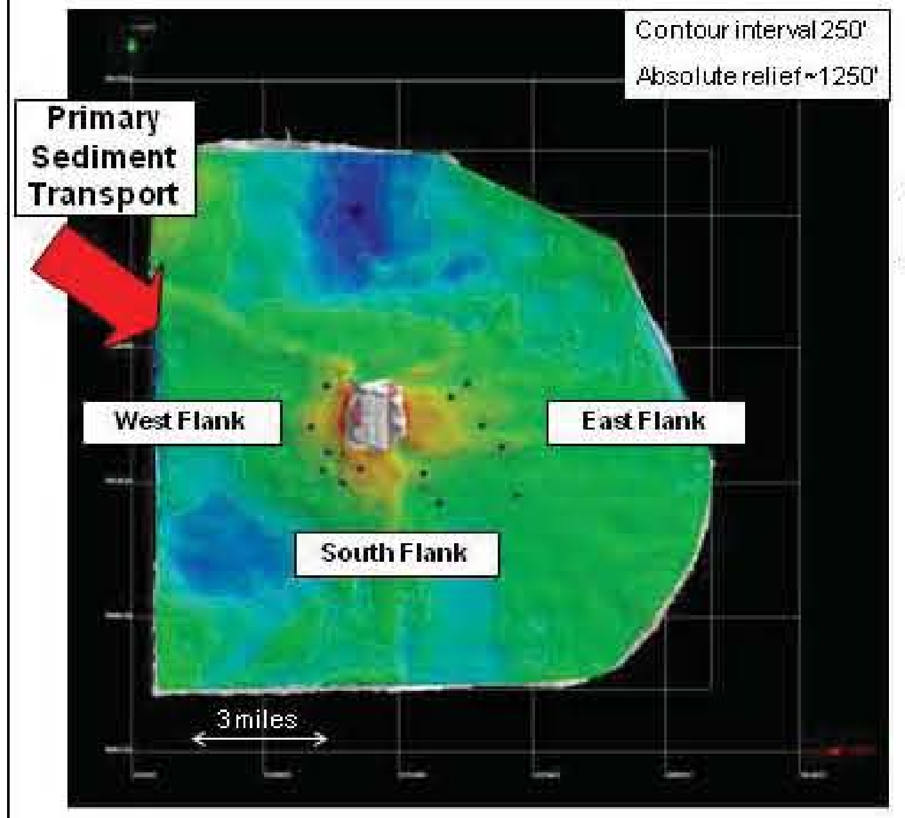
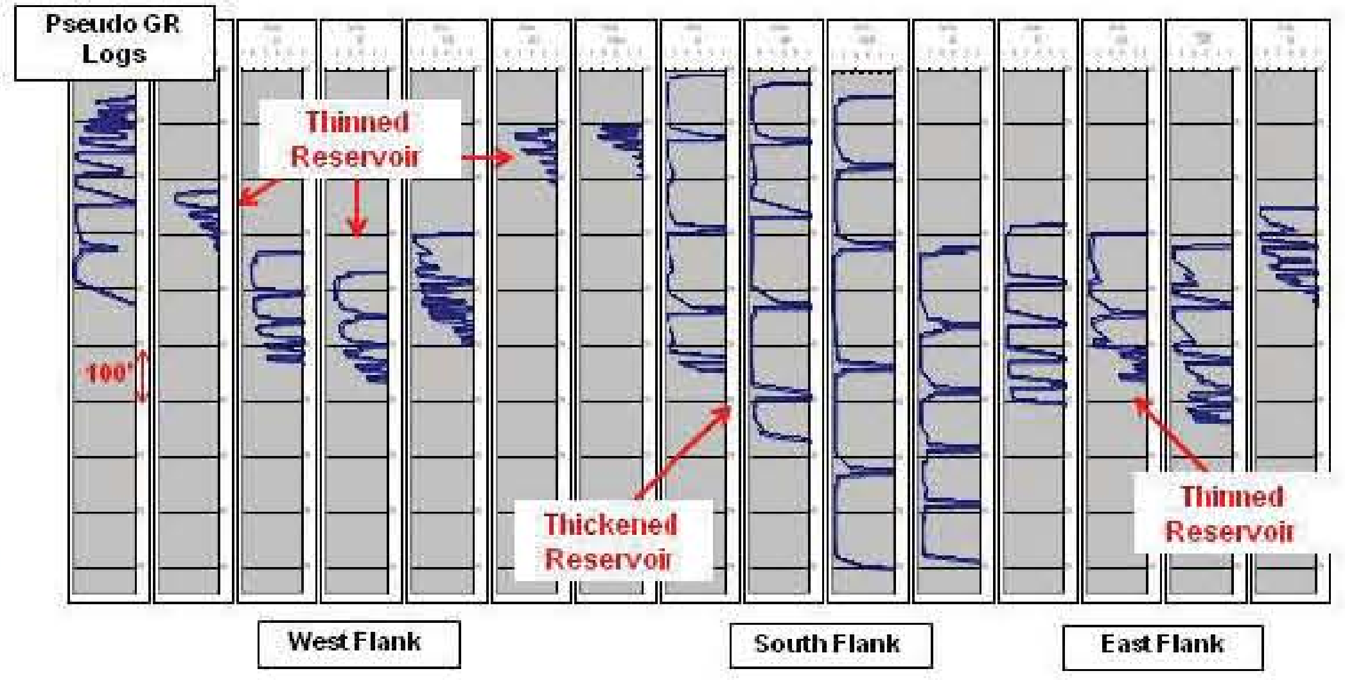
Impact of Restored Paleotopography Scenarios on Deposits

Multiple scenarios of topography have been generated, based on density of mapped sequence boundaries (M7, M9, M10). Each of these paleotopographic scenarios has been tested via simulation of reservoir deposition. Pseudo GR log predictions on the west, south, and east flanks of the paleohigh are shown for each scenario below. Note that the M9 full-scale paleotopography simulation includes 5 cycles of deposition as compared to 3 cycles for the others.

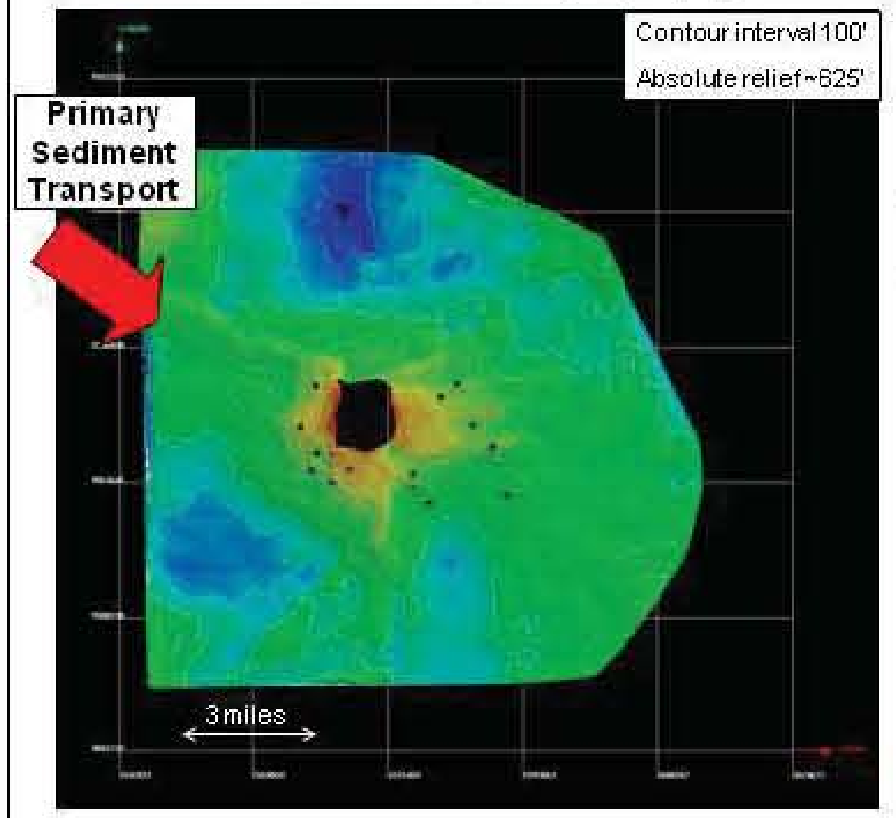
**M9 (Restored to M7)
Full-Scale Paleotopography**



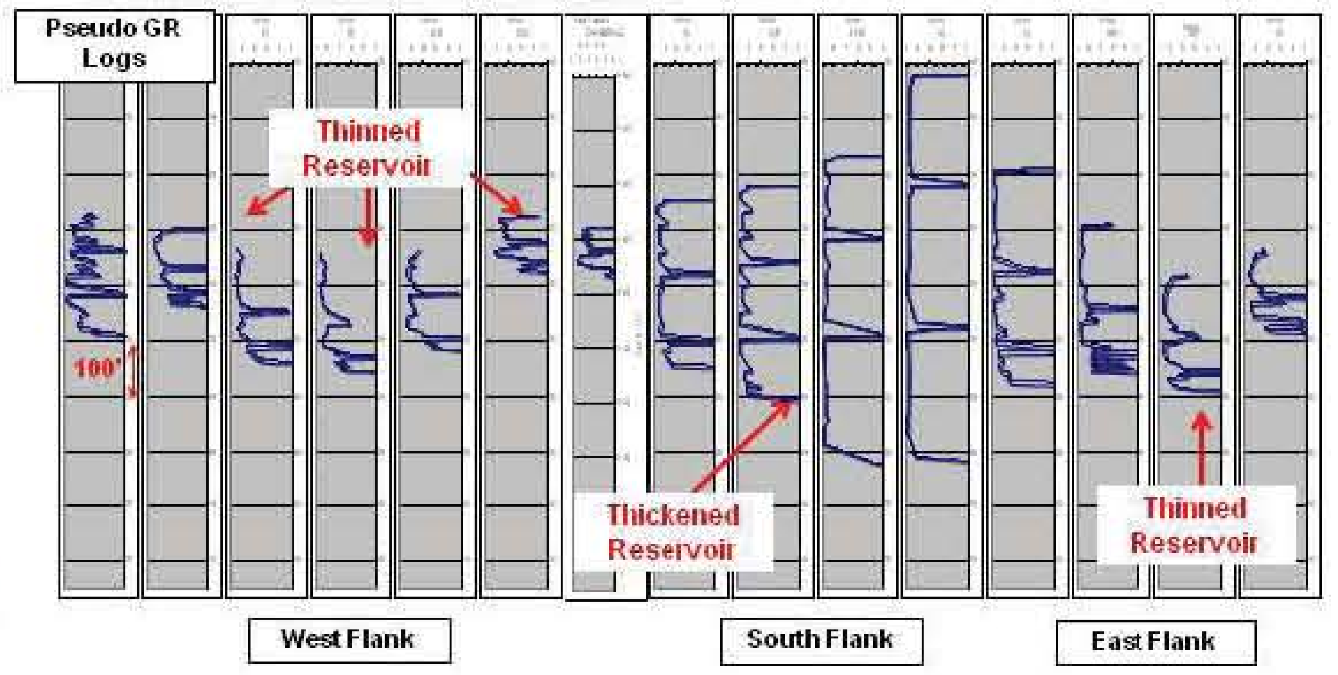
The M9 full-scale paleotopography simulation generally exhibits thinned reservoir high on paleotopography (west flank) and in the distal lee (east flank) of the structure. Thickened reservoir exists on the south flank directly down-transport of the paleohigh.



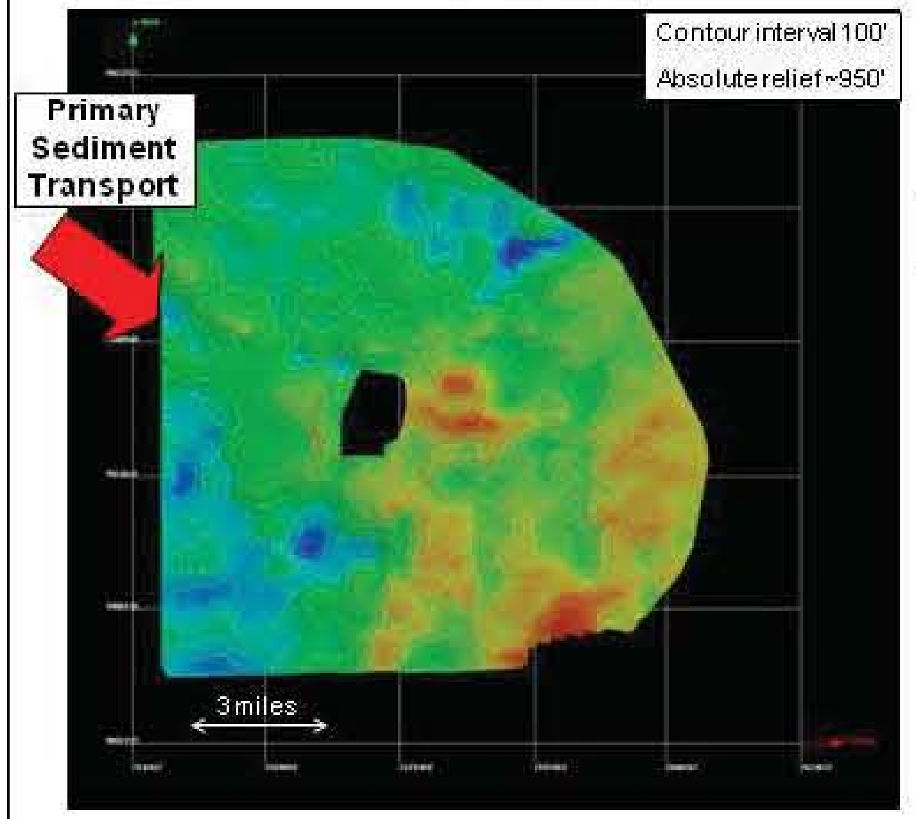
**M9 (Restored to M7)
Half-Scale Paleotopography**



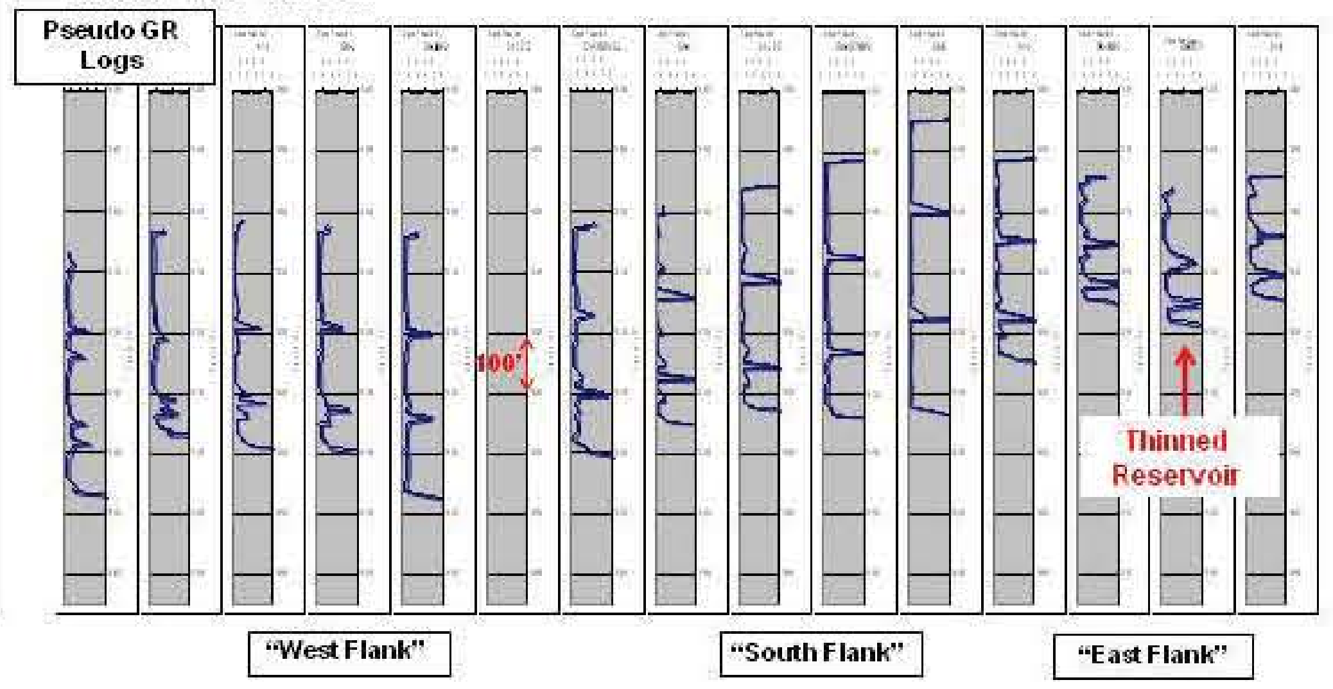
The M9 half-scale paleotopography simulation exhibits relative thickness changes similar to the M9 full-scale paleotopography above but the absolute difference between the flanks is less. This is as expected since the relative difference between flow height and paleotopographic relief is less, and therefore paleotopography has a smaller impact on the deposits. These results are closer to well control.



**M10 (Restored to M9)
Paleotopography**

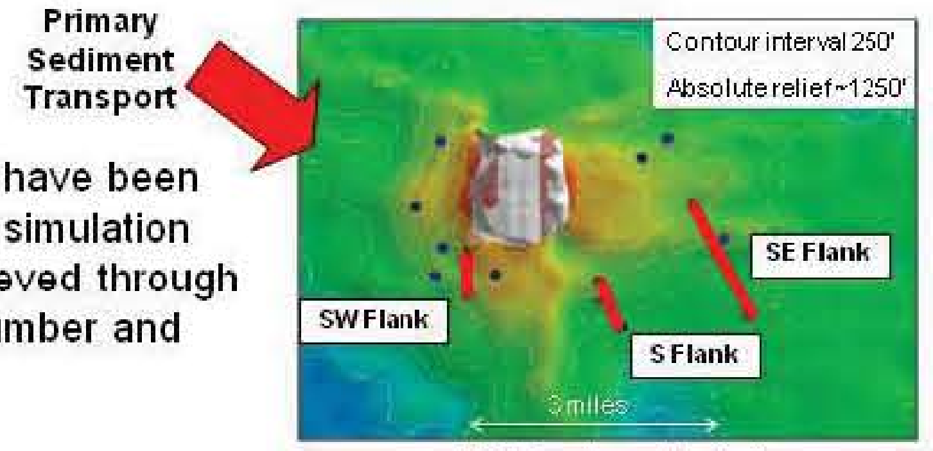


The M10 paleotopography infers less of a paleohigh in the central area as compared to the M9 scenarios. This causes the simulation to exhibit less changes in reservoir thickness except in the more distal penetrations to the east that sit on a different paleohigh. The "west flank" predictions here are too thick compared to the wells but those on the "south flank" and "east flank" are closer.



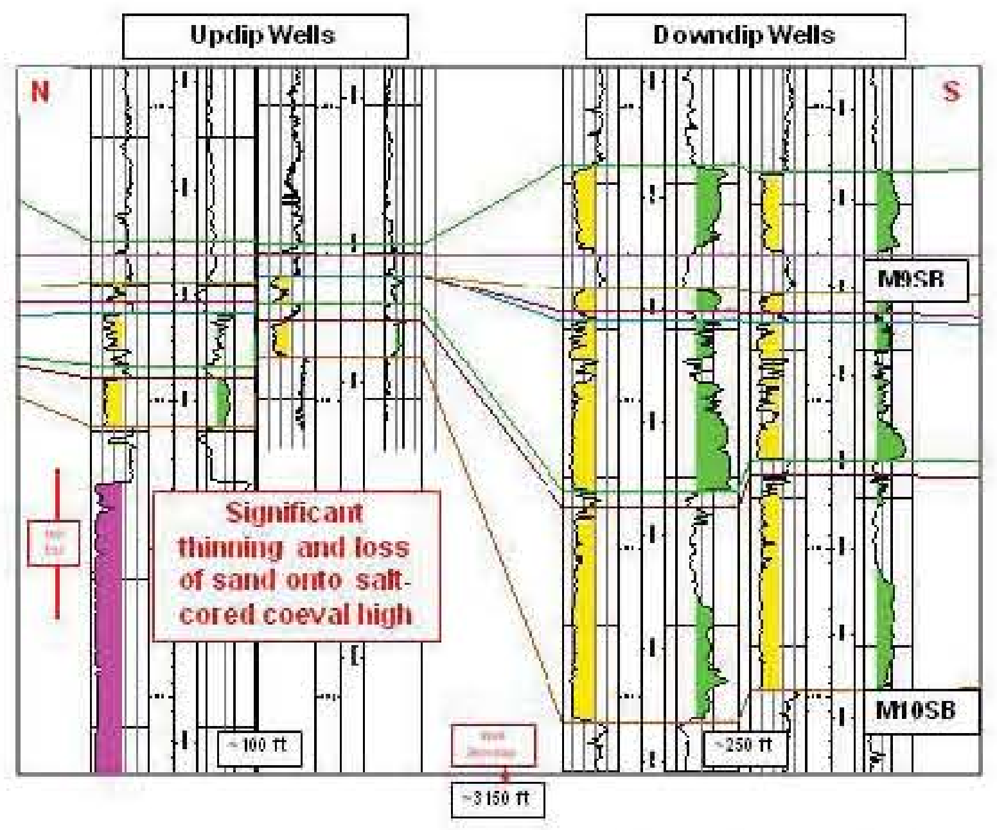
Predictions Versus Well Results

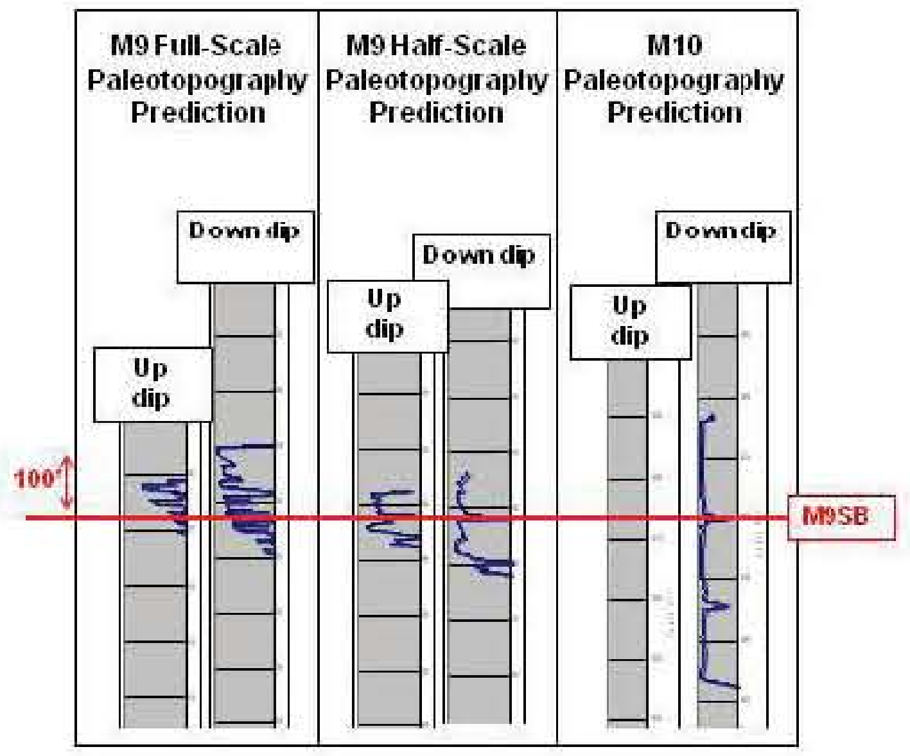
Estimates of the absolute magnitudes of paleotopographic relief have been tested by the degree of similarity of drilled well penetrations and simulation predictions. Reasonable matches to well penetrations were achieved through step-wise modification of the paleotopographic scenarios and number and character of turbidite flows making up each reservoir.



M9 (Restored to M7)
Full-Scale Paleotopography

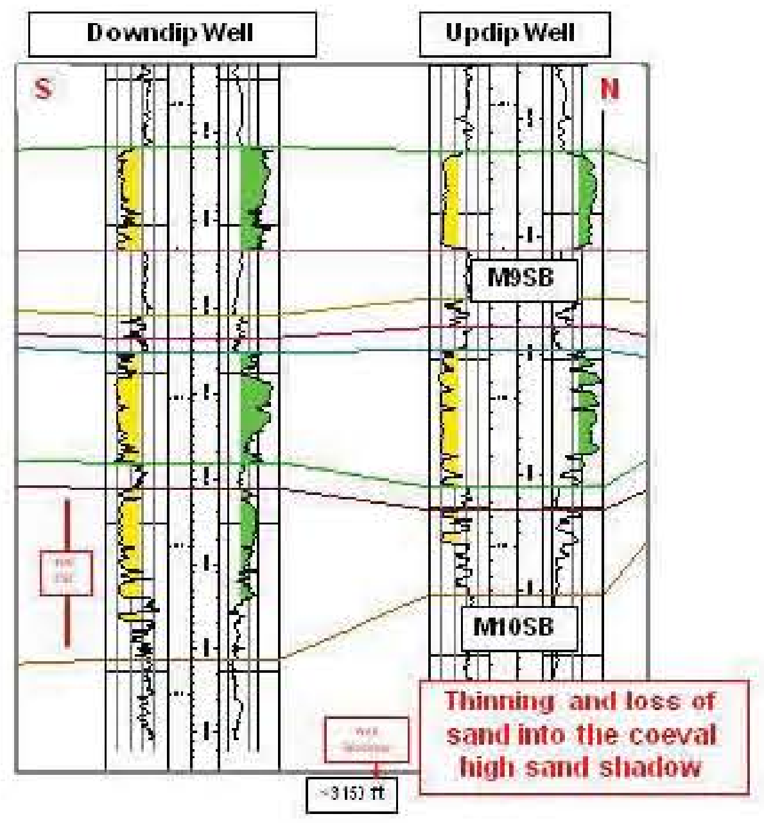
Southwest Flank

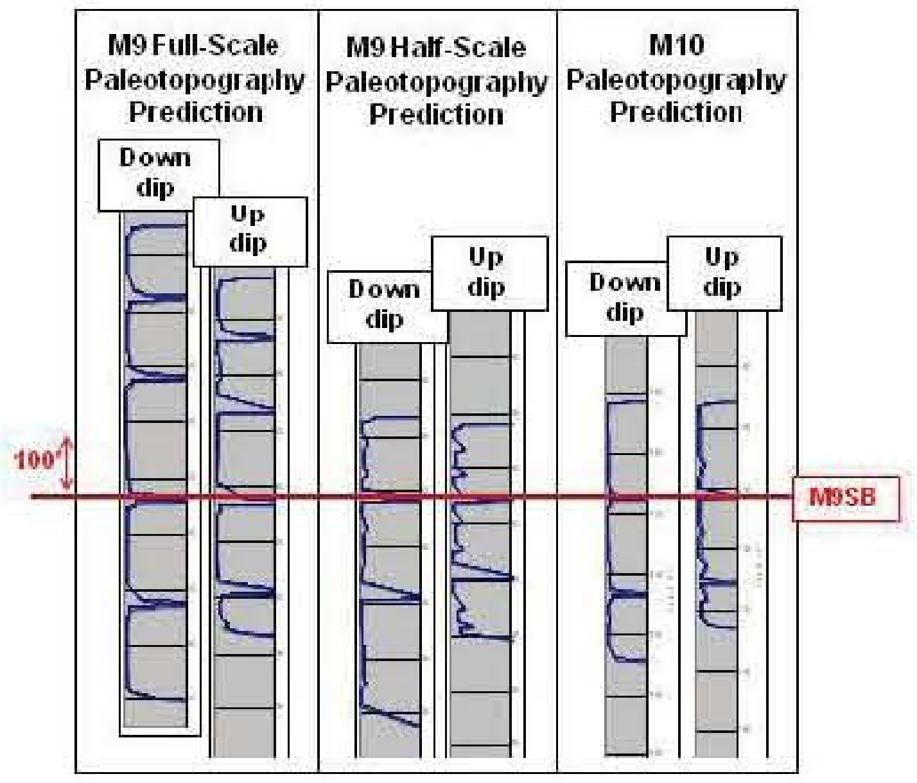




Significant thinning and loss of sand onto the salt-cored coeval high is predicted on the southwest flank, though only the M10 simulation matches the well off paleostructure closely.

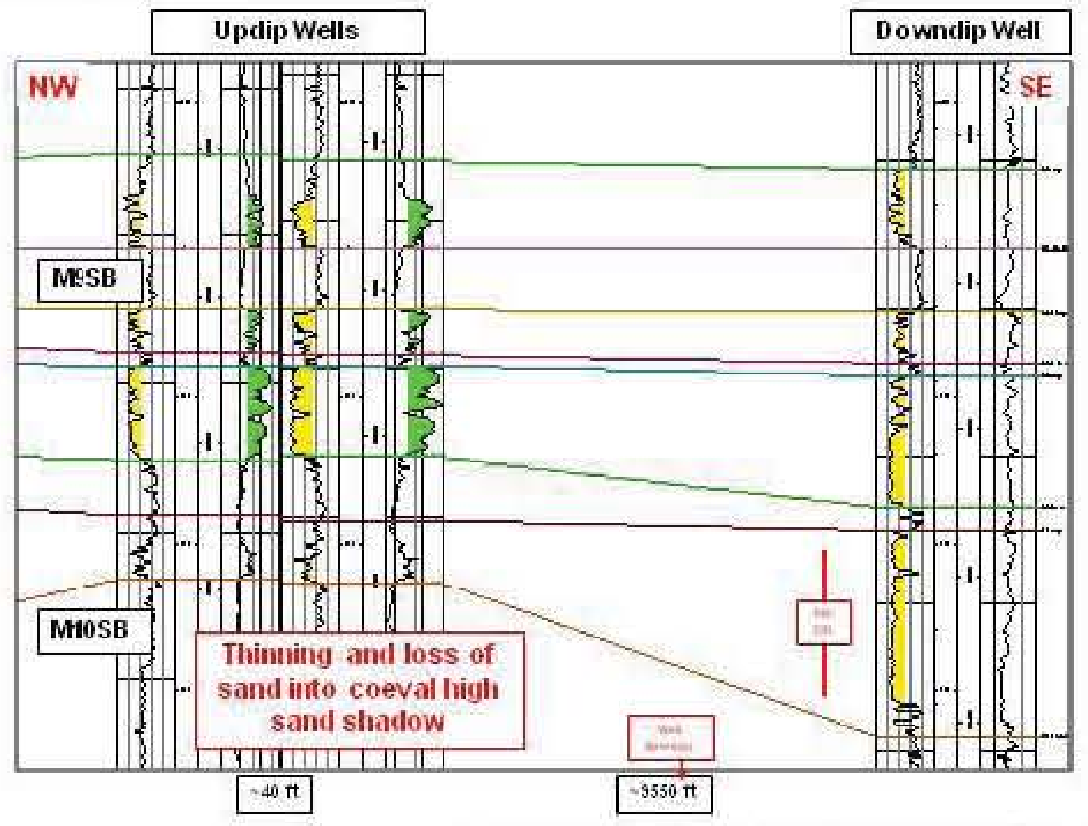
South Flank

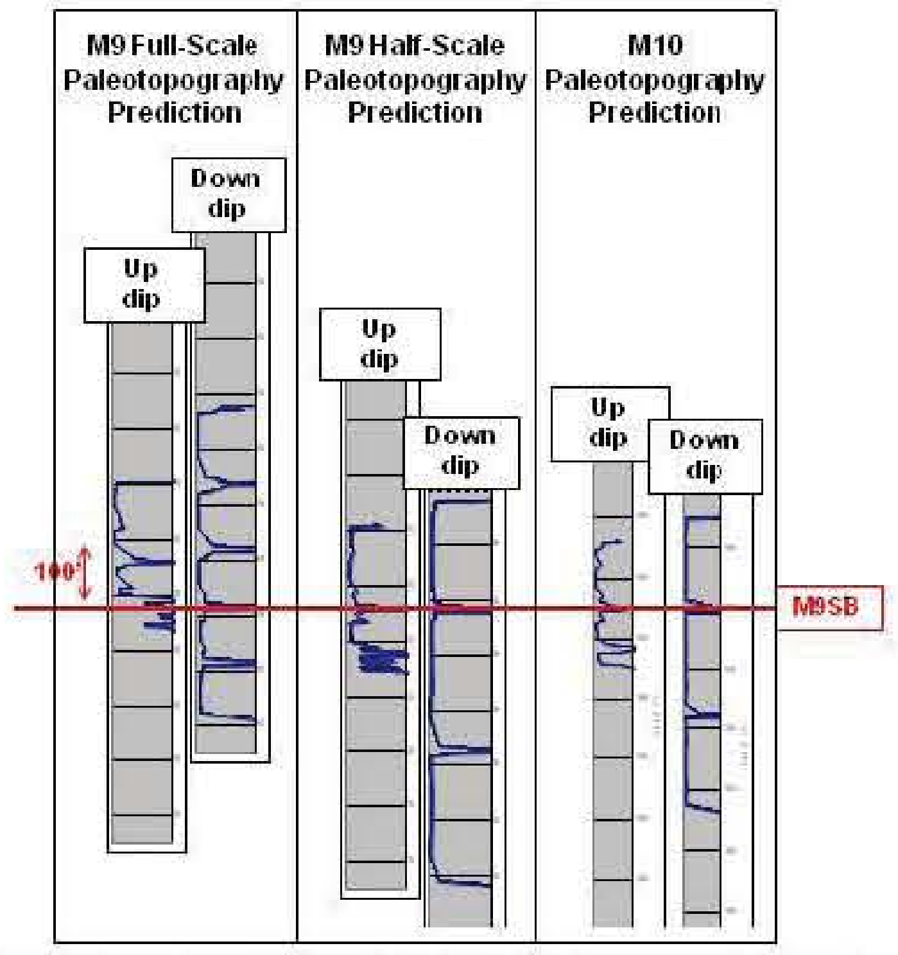




Thinning and loss of sand into the coeval high sand shadow is predicted on the south flank, though again the M10 simulation matches the well thicknesses the best.

Southeast Flank





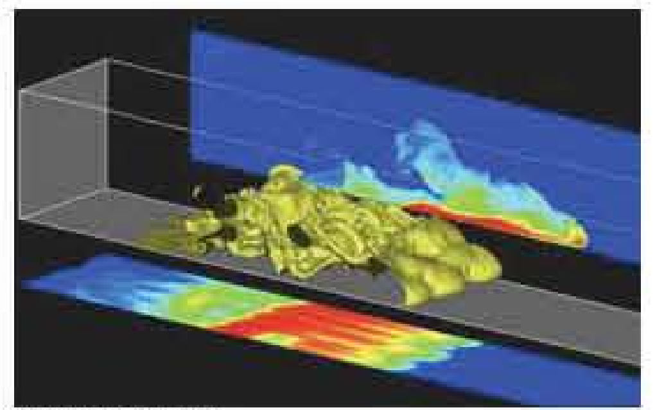
Thinning and loss of sand into the coeval high sand shadow is predicted on the southeast flank, though again the M10 simulation matches the well thicknesses the best.

Conclusions

1. Lower Miocene turbidite reservoirs drilled in the Western Atwater Fold Belt, Gulf of Mexico, exhibit significant variations in gross reservoir thickness, character, and quality within individual fields on salt-cored structural highs, and these variations can often be related to presence of significant paleotopography during deposition.
2. Understanding the interaction between substrate topography and turbidite sedimentation is critical in attempting to quantitatively predict reservoir variation within these fields.
3. A new technique to help predict these turbidite reservoir variations is to first perform structural restoration to infer paleotopography, and then simulate deposition on that paleotopography.
4. Reasonable matches to well penetrations were achieved through step-wise modification of the paleotopography scenarios and number and character of turbidite flows making up each reservoir.
5. The critical factors that produce variations in the character of turbidite flow deposits around obstructing topography are relative flow height with respect to paleorelief and flow trajectory relative to paleotopography.
6. Given the uncertainty in multiple parameters (e.g. number of flows, flow width, flow height, flow volume, grain size distribution, and parameter variation from flow to flow) it is important that multiple screening scenarios be simulated and multiple well penetrations be matched successfully before having reasonable confidence in additional inter-well predictions.
7. The rapid simulation capability available with depth-averaged simulations enables this testing of multiple scenarios in a reasonable time frame.

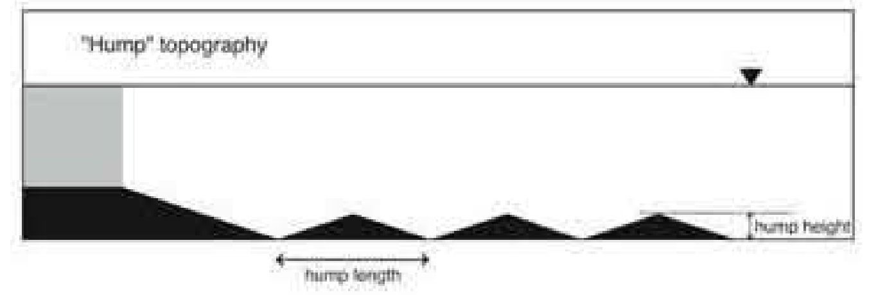
Modeling Turbulent Flow More Realistically

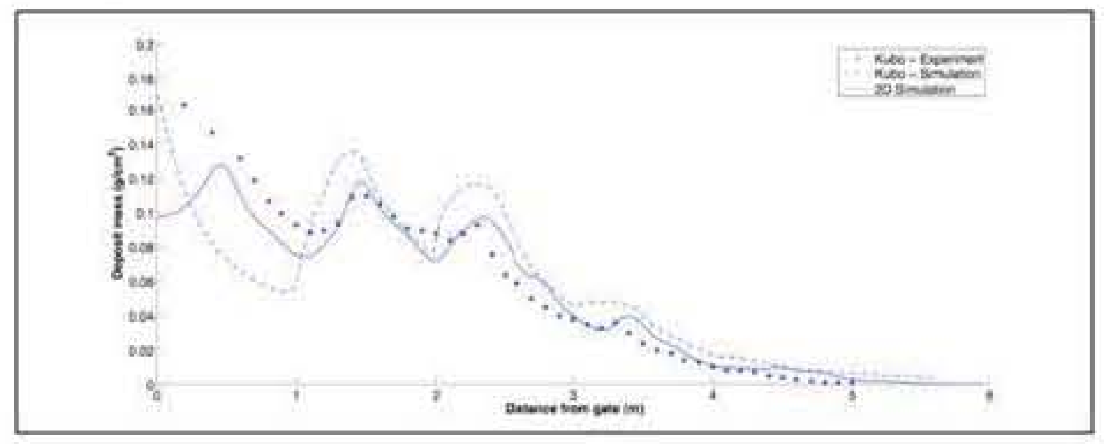
Direct numerical simulations that explicitly model turbulent flow have also been run, and are continuing to be further benchmarked and developed. There are however issues with the amount of computing power needed and the simulation run times. It is recommended that primary parameter and scenario testing be done with depth-averaged simulations before running more explicit simulations such as those shown below.



Necker et al (2002)

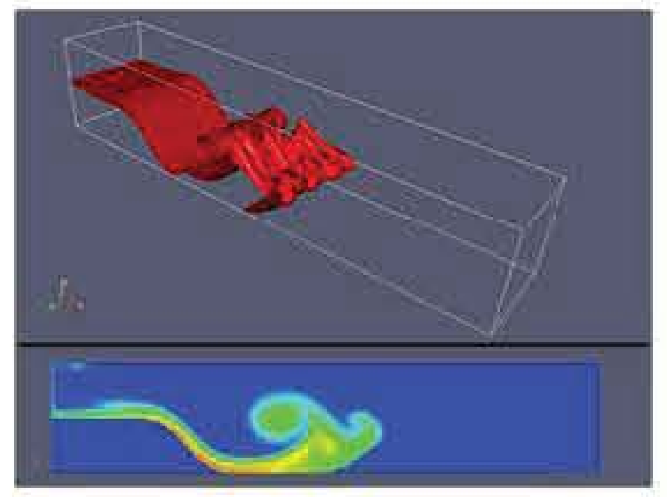
Benchmarking Against Physical Experiments (Kubo, 2004)



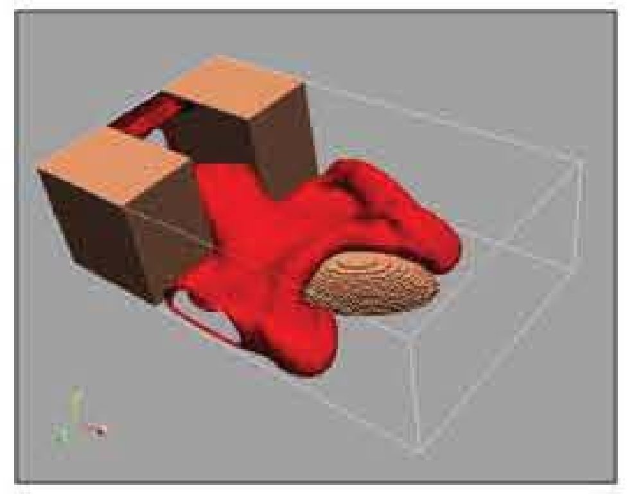


Evolving From More Simple to More Complex Topography

Flow Over a 2D Barrier



Flow Over a 3D Bump



Flow Over Realistic Topography