

3-D Interpretation of the Reservoir Property Distribution in the Belle River Mills Silurian (Niagaran) Reef, St. Clair County, Michigan*

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Abstract

Silurian (Niagaran) reefs are significant hydrocarbon reservoirs in the Michigan Basin, having produced over 470 MMBO and 2.75 trillion cubic feet of gas. The primary production for these reservoirs is generally low, averaging about 25%, due to their complex internal heterogeneities. 3-D static reservoir models that incorporate detailed facies and sequence stratigraphic interpretations enhance the understanding of the spatial distribution, and possible controlling mechanisms, of reservoir properties. A model created in a study of the Belle River Mills (BRM) Reef, located in St. Claire County, MI, tested modeling parameters, such as variograms, cell sizes, layers, and sequence stratigraphic constraints, to determine which set of parameters ultimately produced the most geologically reasonable model of the BRM reef reservoir. Results of the study indicate that 300 proportional layers and variograms with ranges of 500 feet produce the most geologically representative models of the distribution of facies and reservoir properties throughout the BRM reef. The model illustrates a geometrically well developed windward margin at the southeastern edge of the reservoir, with higher porosity and permeability values apparent on the eastern margin of the reef. The incorporation of a sequence stratigraphic framework and detailed facies analysis help to improve the geologic integrity of 3-D static reservoir models and have the potential to enhance primary and secondary production from Michigan Basin Silurian Reef reservoirs.

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Presenter's Notes: Reservoir Property Distribution is defined in this study by the porosity and permeability values taken from whole core analysis

Research Objectives

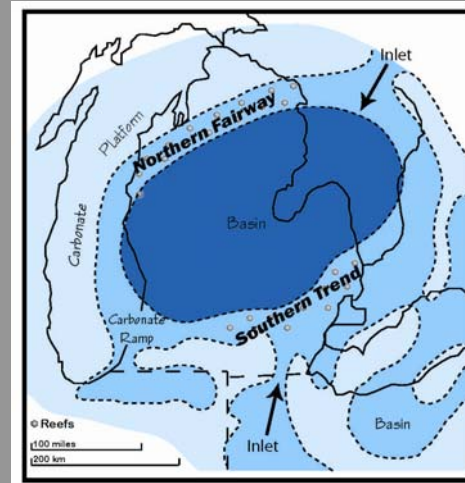
- Create a 3-D rock-based model illustrating the lateral and vertical distribution of facies and reservoir properties
 - Demonstrate predictability, and enhance understanding of facies, reef architecture, and reservoir properties
 - Sequence stratigraphic control
 - Windward vs. leeward variability
- Improve production from Silurian (Niagaran) reef reservoirs in the Michigan Basin, which are still targeted for exploration and production

Presenter's Notes: The 3-D model helped to increase the understanding of reservoir predictability as a function of sequence strat and windward/leeward control

Windward-leeward variability in the distribution of facies geometry and resulting reservoir quality

Reef Trends in the Michigan Basin

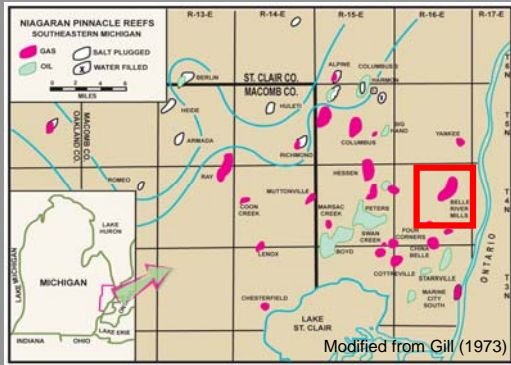
- Broad, basin-centered subsidence occurred during the Silurian
 - Created a shallow, intracratonic sea
 - Three major zones of deposition identified
 - Silurian-aged pinnacle reef growth occurred along the distal portion of the carbonate ramp
- Hydrocarbon Production:
 - Over 470 MMBO oil and 2.75 TCF gas



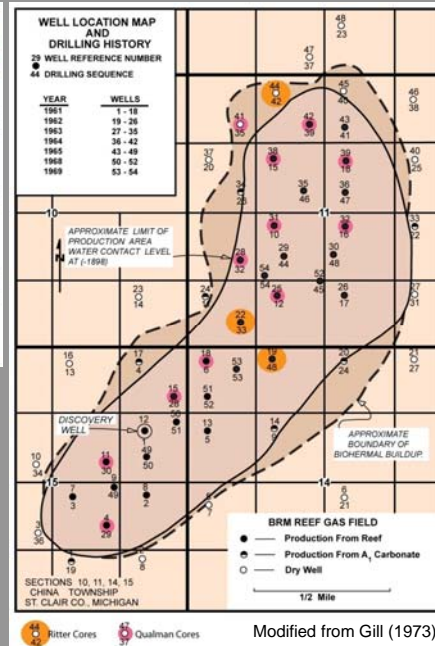
Modified from Briggs *et al.* (1980)

Presenter's Notes: Michigan Basin located at approx 25 S latitude during the Silurian – warm tropical environment

Belle River Mills



- Discovered in January of 1961
- 43 original wells were drilled
 - 26 wells produced 21.4 BCF gas
- 11 additional wells drilled in 1965 when the reef was converted to a gas storage facility



Previous BRM Models

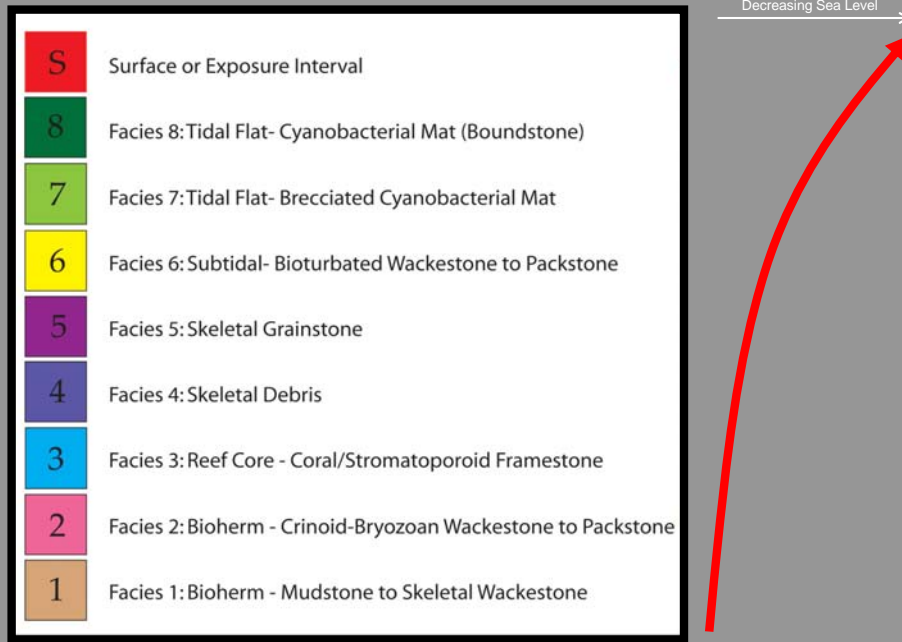
- Balogh (1981)
 - Vertical heterogeneity recognized; lateral heterogeneity not acknowledged
- Gill (1973)
 - Vertical heterogeneity recognized; lateral heterogeneity uncertain
- Wylie and Wood (2005)
 - Layer-cake internal architecture

Methodology

- Identify key depositional facies in the BRM reef
- Develop a sequence stratigraphic framework
 - To constrain the model to probable chronostratigraphic surfaces
- Analyze porosity and permeability within the sequence stratigraphic framework
- Develop 3-D Facies and Petrophysical models using Schlumberger's Petrel (geostatistical) modeling software

Presenter's Notes: Identify the key depositional facies, which show a correlation to reservoir properties
Develop a sequence strat framework – which is shown to have control on reservoir property distribution
3-D models increase visualization of facies and, therefore, property distribution in the reservoir

Idealized Facies Stacking Pattern



Presenter's Notes: Each depositional facies corresponds to relative sea-level so that increased facies # = decreased sea-level

Facies 1 & 2 dominate bioherm area, but are intercalated with facies 3, 4, and 5

Facies 3, 4, and 5 dominate the "reef" area, but intercalated with 1 & 2 near base and 6, 7, & 8 near top

Facies 6, 7, and 8 make up the "supratidal island – top reef" surface

"S" facies – surfaces – appear at the top of sequences or indicate pauses in sedimentation

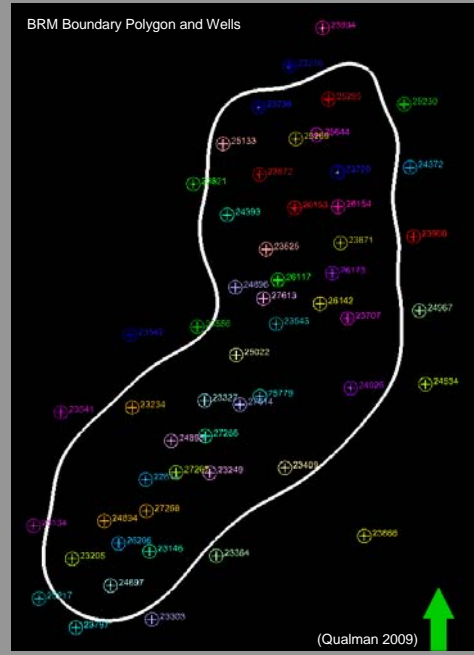
Constructing the Model in Petrel 2007

- Contains nearly 7 million 15' x 15' cells
- Wireline log data from 37 wells
- Facies data from 15 wells with core
- 300 proportional layers
- Utilizes a 500' variogram
- Lateral facies distribution controlled by horizontal probability maps
- Constrained by sequence stratigraphic surfaces
- SIS (facies) & SGS (petrophysical) algorithms

Presenter's Notes: Ultimately, all facies and seq strat data were applied to a 3-D geostat model of the BRM reef
Stochastic algorithms used to interpolate facies and reservoir property distribution between the data points

Boundary Polygon

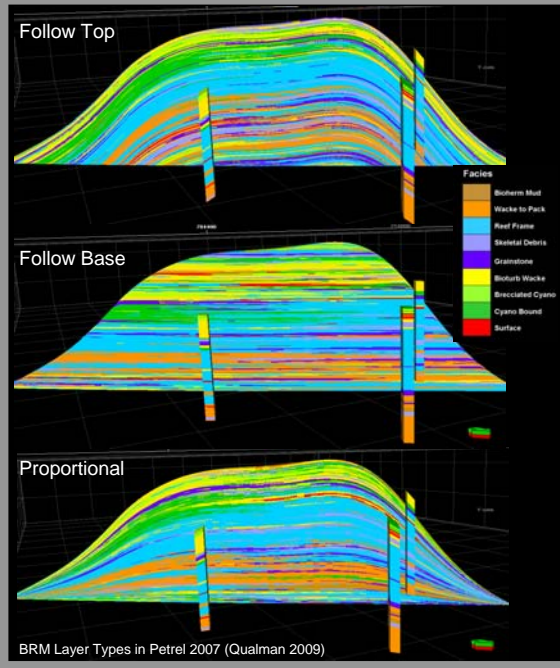
- Represents Gill's interpretation of the approximate boundary for the bioherm
- 17 of the 54 wells are beyond the margin of the boundary
 - Not included in the model



Presenter's Notes: As previously mentioned, the bioherm boundary, determined by Gill (1973), was used to constrain the geometry of the model

Layers

- Follow top
 - Layers follow the geometry of the top surface (horizon)
- Follow base
 - Layers follow the geometry of the base surface (horizon)
- Proportional
 - Layers honor both top and bottom surfaces (horizons)



Presenter's Notes: Follow top does not honor the base surface, though the reef grew from the bottom up

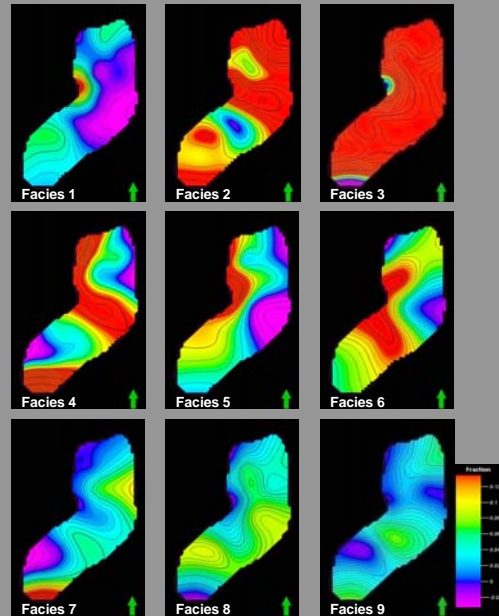
Follow base appears too layer-cake and horizontally continuous

Proportional layers honor both the top and base surfaces and provide the best representation of the three options available, based on observations from previous studies of outcrops and subsurface data, and from core observations in the current study

Layers should be selected based on the expected distribution of facies and properties within a reservoir, as well as dominant expected flow characteristics – in a diff. depositional setting, such as a carb ramp (Yucatan), follow base may be a more appropriate layering choice for a model.

Facies Probability Maps

- Constrain the lateral variability of facies distribution
- Reflective of the proportion of each facies observed in core
- Illustrate the lateral variability of each facies throughout the entire reef complex

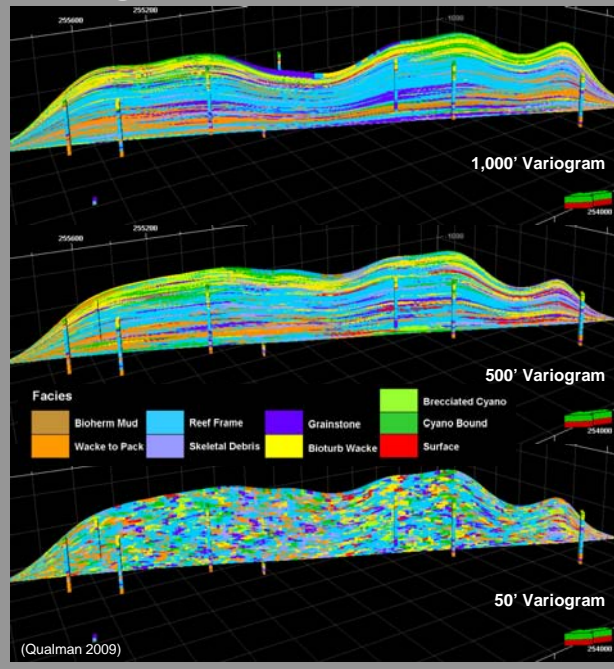


Facies Distribution Probabilities (Qualman 2009)

Presenter's Notes: Maps depict the significant lateral variability of facies expected within the reef and help the program with modeling lateral facies variability based on core analysis

Variograms

- Measures how far away from a data point dissimilarity can be calculated
- 1,000' and 500' similar
 - 500' shows higher lateral variability
- 50' shows extreme heterogeneity



Presenter's Notes: A fundamental characteristic of carbonate deposition systems is lateral variability of facies and properties.

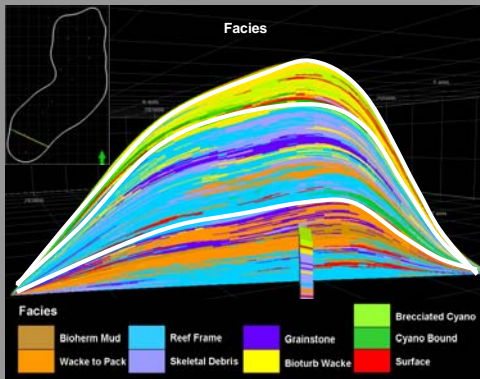
It is important to define the variogram length which is used to control the maximum distance that values can be correlated to a known data point.

500' shows more variability as expected and was chosen based on well spacing of 1000' (ave) – so data is correlated to the closest known data point within the reef.

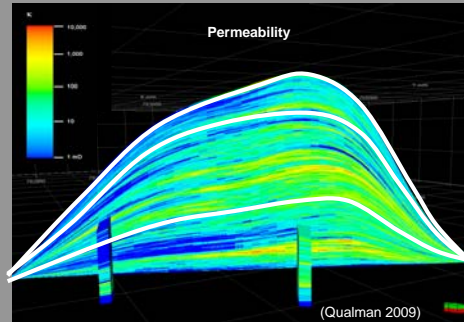
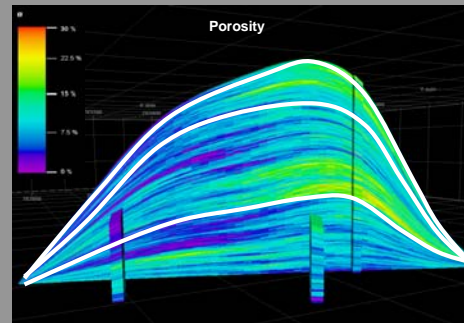
50' chosen based on Pranter et al. (2005) [sheep canyon ramp in Wyoming, Mississippian] stating that variance within carbonate systems occurs at 10's of feet

Borgomano et al. (2008) [carbonate ramp-like systems, Malampaya] state smallest scale geologic models not necessary – have little effect on fluid flow of model – need to construct the model at the scale of the correlated structures between wells – in this case, sequence stratigraphic boundaries/chronostratigraphic surfaces

Sequence Stratigraphic Constraints



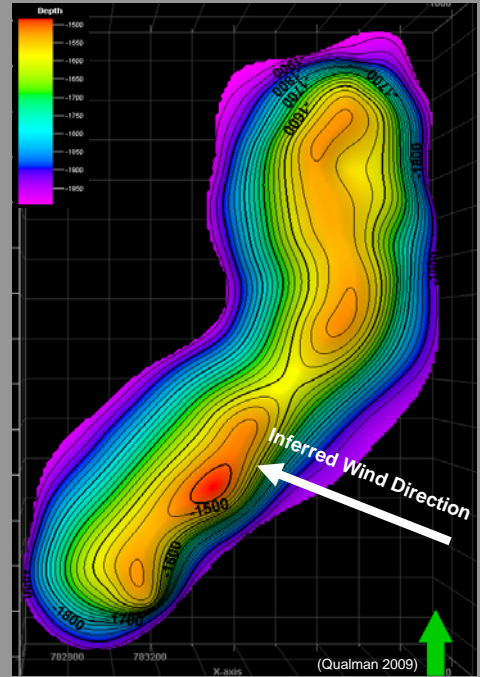
- Facies model constrains facies distribution based on core observations
- Model shows higher order cyclicity within 4th order boundaries
- Correlation between facies and reservoir properties



Presenter's Notes: Wide distribution of bioherm facies with capping grainstones, then a flooding surface with more bioherm topped by more capping grainstone – representative of higher frequency cycles within the 4th order HFS?

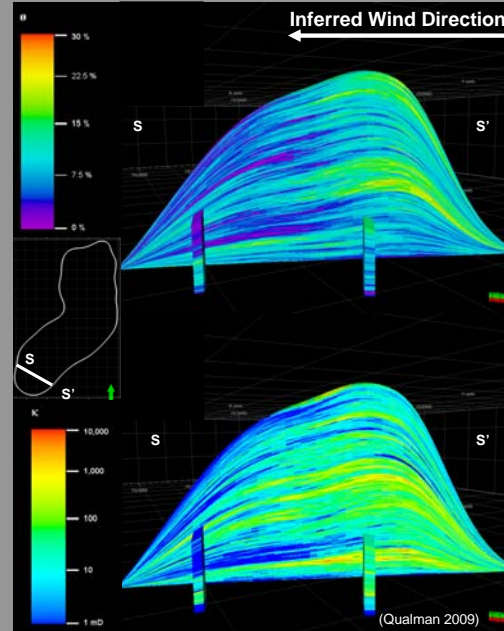
Reef Geometry

- BRM reef is a steep-margined reef complex
 - High-angled slopes at the northwest (60°) and southeast (75°)
 - Geometry possibly reflective of windward/leeward reef development
 - Paleogeography and paleoclimatology indicate the Michigan Basin was subject to southeasterly trade winds during the Silurian

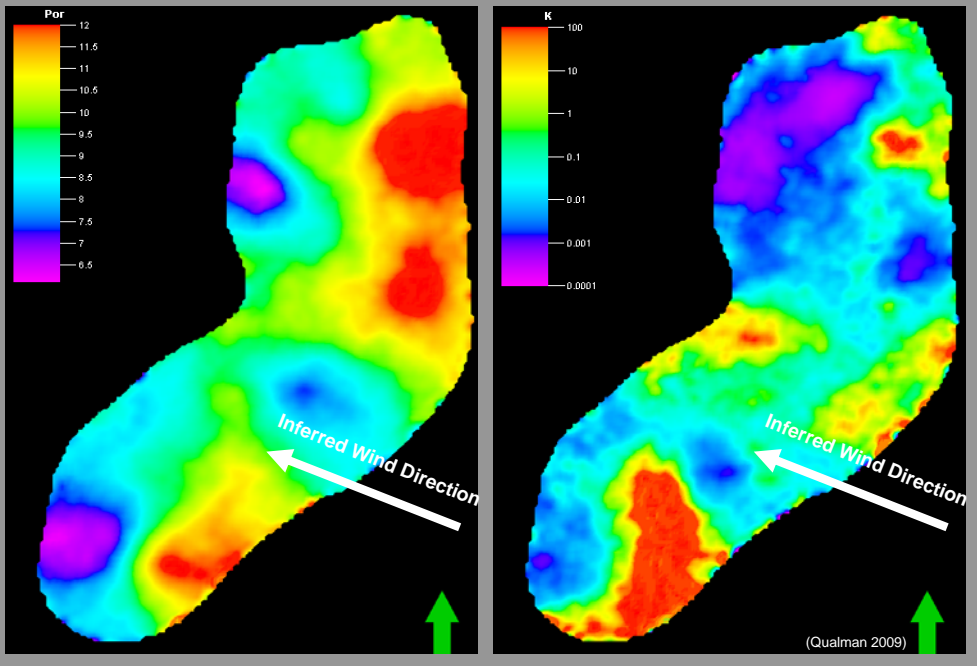


Windward/Leeward Property Distribution

- Increased porosity and permeability occurs along the east margin of the reef
- Property distribution and reef geometry further support the observation of windward-leeward reef development



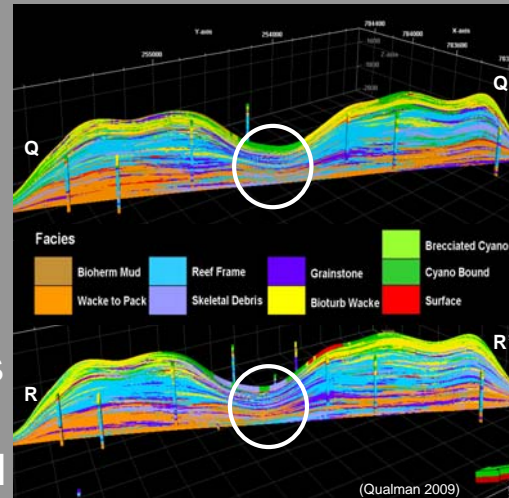
Lateral Reservoir Property Distribution



Presenter's Notes: Average maps of porosity and permeability showing highest porosity and permeability mostly located along the windward margin. Anomalous low porosity on the windward margin associated with a lack of data (no well).

Testing Model Accuracy

- Models with (R-R') and without (Q-Q') data from Ritter's (2008) wells
- Facies and properties are reasonably distributed away from the known data points
- Enhanced well control leads to higher resolution models



Presenter's Notes: The original model containing data from the 12 cores analyzed in the was tested against a model incorporating data from three additional wells analyzed in the study by Ritter (2008)

Initial model isn't changed a lot – but the Ritter cores give higher resolution/more detail

Mode to some extent accurately illustrates the distribution of facies and res properties (with proper constraints)

Increased well control will lead to higher resolution models where geologic reasonability is constrained by a larger data set

Conclusions

- Incorporation of sequence constraints depict probable sequence stratigraphic control on the distribution of facies and properties
- The study identifies a probable windward-leeward distribution of facies and reservoir properties
- SIS and SGS methods used in the BRM model create geologically reasonable distributions of facies and reservoir properties away from the data points
 - Increased well control leads to higher resolution models

Presenter's Notes: Sequence boundaries seem to have some control on reservoir property distribution, where 4th order HFS boundaries are associated with increased por/perm

In Summary

- Models represent general interpretations of reservoir property and facies distribution
 - Better depicts the vertical and lateral heterogeneity within the BRM reef
- Modeling parameters should be carefully considered for the reservoir of interest
 - Constraining the model to core increases the accuracy
- Results of the study may be applicable to other reefs and build-ups
- Results may increase production efficiency through enhanced understanding of reservoir property distribution

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