3-D Numerical Stratigraphic Forward Modeling of Rifts: Characterizing Reservoir Presence Risk

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Objectives
Why Model Rifts?

Rift environments feature:
• Compressed spatiotemporal scales for a wide range of depositional processes
• Complex non-linear interaction of climate, tectonics, and deposition
• Ideal setting to demonstrate how to characterize uncertainty of exploration and production risk elements:
  – Reservoir, Hydrocarbon Source, Structure/Geometry, & Seal

b. Rift with sag basin

Lateral migration of hydrocarbons at base of sag basin

Tilted fault block trap too deep
Viable trap
Viable trap

Good top seal

Broad region where source rocks are mature

Drape anticline in post-rift basin

Morley et al., 1990
Controls on Facies Distribution
Structure, Climate, & Chemistry are linked

- Extension, Subsidence and uplift rates
- Structural control on drainage

- Traps
- Migration Pathways
Controls on Facies Distribution
Structure, Climate, & Chemistry are linked

- Water flux
- Sediment flux
- Point source location

- Volume of water
- Precipitation-Evaporation
- Lake and sea-level changes
- Stratification

Moore et. al., 2005
Bohacs et. al., 2000
Controls on Facies Distribution
Structure, Climate, & Chemistry are linked

- Water stratification
- Water circulation
- Water temperature

Nutrients
Salinity
Alkalinity
Weathering
Numerical stratigraphic models use physical laws to simulate the movement of water and sediment.

Advantages of modeling studies include the ability to:
- Integrate data and test conceptual tectono-stratigraphic frameworks
- Develop depositional frameworks grounded by physical relationships
- Explore the parameter space

Modeling studies are limited in that:
- Mechanisms of physical processes are the subject of ongoing research
- Transition from morphology (surface) to stratigraphy (subsurface) is poorly understood
- Computational limitations require simplifying assumptions and data averaging
Previous Work
Testing tectono-stratigraphic concepts

Fault slip rates

Source-to-Sink

Contreras and Scholz, 2001
Smith, 2013
Hardy and Gawthorpe, 1998
1. The structure model was developed with Dynel3D, a product of Schlumberger. Dynel3D is an elastic finite element package designed for structural geology applications (Maerten & Maerten, 2006).

2. 7 faults dipping at ~40 degrees and ranging from 50-100 km long were placed in a 30 km thick crust. Faults are treated as frictionless sliding contact interfaces that do not nucleate or propagate.

3. The model, with dimensions ~350 km x 350 km is subjected to 10 km (~3%) lateral extension. Fault slip results, which produces hanging wall (basin) subsidence and footwall uplift.
4. The crust is treated as an infinitely strong elastic layer, thus necking processes are limited. The model is intended to approximate the early stages of syn-rift deformation.

5. The structure model does not account for mantle interaction and deformation rates are assumed constant through time.
1. The stratigraphic model was developed using DIONISOS (Diffusive Oriented Normal and Inverse Simulation Of Sediments), a product of IFP Energies Nouvelles. DIONISOS is a nonlinear diffusion-based sediment transport model which simulates the complex interaction of tectonism, climate, base level, and autogenic processes (Granjeon, 2014).
2. The structure model from Dynel3D was re-gridded and used as a subsidence/uplift map. DIONISOS cannot perform lateral extension in opposing directions simultaneously. Note that the 10 km of extension in the structure model would be accommodated within two cells (5 km) of the stratigraphic model.
Basin Evolution
Sand %
1) Axial delta

2) Transverse system cutting through uplifting footwall

3) Transfer zone drainage

4) Axial deltaic setting

5) Footwall incision


6) Axial fluvial setting

7) Transverse deltaic setting

8) Transverse fluvial setting

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## Modeled Scenarios for Uncertainty Analysis

<table>
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<tr>
<th></th>
<th>25</th>
<th>33</th>
<th>40</th>
<th>48</th>
<th>55</th>
<th>62.5</th>
<th>70</th>
<th>77.5</th>
<th>85</th>
<th>92.5</th>
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<tbody>
<tr>
<td><strong>Lake Level Amplitude (m)</strong></td>
<td></td>
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<tr>
<td><strong>Lake Level Periodicity (kyr)</strong></td>
<td>50</td>
<td>65</td>
<td>80</td>
<td>95</td>
<td>110</td>
<td>125</td>
<td>140</td>
<td>155</td>
<td>170</td>
<td>185</td>
<td>200</td>
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<tr>
<td><strong>Sediment Supply (km³/Myr)</strong></td>
<td>500</td>
<td>650</td>
<td>800</td>
<td>950</td>
<td>1100</td>
<td>1250</td>
<td>1400</td>
<td>1550</td>
<td>1700</td>
<td>1850</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Water (m³/sec)</strong></td>
<td>250</td>
<td>325</td>
<td>400</td>
<td>475</td>
<td>550</td>
<td>625</td>
<td>700</td>
<td>775</td>
<td>850</td>
<td>925</td>
<td>1000</td>
</tr>
</tbody>
</table>
Explore Parameter Space

- Model runs take a single set of input parameters: one each of sediment and water supply, base level curve, etc.

- Input values are constrained but generally not exactly known

- Multiple model runs explore the sensitivity of results to the input values within the bounds of specified constraints

- Sensitivity analysis reduces uncertainty surrounding the effects of model input values
• Model results at-a-point can be viewed in time or in space

• Temporal metrics answer the question, “How often did the models meet these conditions?”

• Spatial metrics answer the question, “How many of the models meet these conditions?”

• The combination of these metrics characterize deposition: pulses of sand-rich sedimentation vs. steady depositional rate
• Temporal conditional statements are evaluated at each timestep at each point; the final map is the percentage of timesteps meeting the specified condition.

• Spatial conditional statements are evaluated across the entire column height; the final result is a binary map of columns that ‘pass’ the conditional test.

• Conditions may be tailored to basin-specific or economic constraints.
Results: Temporal Conditions

• Conditional temporal metrics quantify how frequently (timesteps/total time) each point meets threshold conditions

• Frequency is calculated for each point within a run and averaged across the full suite of runs

• Final maps show the average predicted probability that a timestep at any given location will meet the conditions, regardless of parameter value
• Conditional spatial metrics use the final isopachs from a model run to determine whether each cell meets threshold conditions.

• Each model is reduced to a binary map and the maps are averaged across the full suite of runs.

• Final maps show the fraction of models which predict that a cell meets threshold conditions.

• Frequencies between 0 and 1 indicate differences among model results.
We use threshold values to determine if model has met a certain condition, e.g.: is there 1 m of deposition with a N:G > 25% at a given timestep?

- Choice of threshold affects probability that a given location will meet the conditions specified

- Threshold values will be basin-specific; the range shown is for purposes of demonstration
Threshold Sensitivity: Spatial

• Analysis of sensitivity of probability maps to threshold values characterizes suite of runs

• These models are most sensitive to N:G value: largest difference in probability maps between 30% and 40% bulk sand fraction, therefore runs are much less likely to predict total sand composition above 30%
Combining Spatial and Temporal Maps

• This map has the 50% probability contour of a spatial conditional map (>25% sand, >25 m total deposition) plotted over a temporal condition (>25% sand, >1 m deposition per timestep) map.

• The two measures are broadly consistent: areas with high total deposition generally correlate to areas of consistent deposition.

• Some areas have low temporal probability, but high spatial probability: this indicates that most of the deposition occurred over a few very active timesteps.
Caveats

• Assumptions of the model
  – Uncertainties in the model
• Have we sufficiently explored the uncertainty space?
  – Were the ranges of inputs too narrow or wide?
• Equal weighting of scenarios
  – Some scenarios are more likely than other, but how much?
• The potential to include unphysical or implausible scenarios
  – Partially due to points 1 and 2
  – Still requires geologic knowledge of setting or basin of interest
Summary and Conclusions

• Numerical modeling provides a quantitative means to test tectono-stratigraphic concepts and develop geologically plausible scenarios.

• The tectono-stratigraphic model successfully reproduced stratal and structural geometries, sand distribution, and sediment routing behavior observed in other models and geologic observations.

• Numerical modeling permits exploration of the parameter space and identification of the dominant controls on sand distribution.

• Sand probability maps use a conditional statement to assess likely presence of sand in a cell at a given time. These types of maps may be extremely useful in industry and academic settings to identify potential drilling locations for resources, carbon sequestration, or Earth system studies.

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