Evolving Finite State Transducers to Interpret Deepwater Reservoir Depositional Environments

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Contents

- Deepwater Reservoir Stratigraphic Interpretation
- Methodology and Workflow
- Well Log Data Set
- Fuzzy Symbols Transformation
- Co-evolutionary Classifiers
- Evolving Finite State Transducers
- Conclusions and Future Work
Deepwater Reservoir Exploration

- Reservoir Characterization
  - reservoir vs. non-reservoir
- Oil Recovery Efficiency
  - The “cost” to recover deposited oil reserve
- One key geological property that can help to answer the two questions is depositional environment
  - The area in which, and physical conditions under which, sediments were deposited.
- One way to utilize depositional information to help characterizing reservoir and predicting recovery efficiency is to compare earth subsurface with similar stratigraphic components.
- In order to conduct this comparative analysis, the first step is to interpret (identify and label) the components based on their depositional signatures.
<table>
<thead>
<tr>
<th>Depositional Information</th>
<th>Gamma Ray Response</th>
<th>Depositional Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive sandstone</td>
<td>Sharp based and blocky</td>
<td>Channel-axis (A)</td>
</tr>
<tr>
<td>Sandstone and shale</td>
<td>Weakly blocky</td>
<td>Channel-off-axis (OA)</td>
</tr>
<tr>
<td>Mix of sandstone inter-bedded with shale</td>
<td>High</td>
<td>Channel-margin (M)</td>
</tr>
<tr>
<td>Shale inter-bedded with sandstone</td>
<td>Irregular</td>
<td>Over-bank (OB)</td>
</tr>
<tr>
<td>Mass wasting (muddy or sandy)</td>
<td>Irregular and chaotic</td>
<td>Mass transport complexes (MTC)</td>
</tr>
</tbody>
</table>

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Well Log Example

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• **Current Approach:**
  – Stratigrapher evaluated the gamma ray log and provided the associated labels based on their domain knowledge.
  – This process is labor intensive and the results may vary depending on the stratigrapher who performed the task.

• **Proposed method:**
  – A computer system that automatically processes gamma ray logs and provides the associated depositional labels.
  – The objectives are to relieve stratigrapher’s workload and to produce more consistent results.
Methodology and Workflow

1. Convert GR well log data into Vsh values
2. Group Vsh data series into segments
3. Align segments produced by computer systems and stratigrapher
4. Assign fuzzy symbols to each segment
5. Calculate attribute values for depositional units labeled by stratigrapher
6. Train 5 classifiers to identify the 5 depositional types
7. Train a FST model that translates fuzzy symbols to associated depositional types

- Innovation: view the process as a language translation process.
- The task is to translate a sequence of symbols from one language (gamma ray log) to another language (depositional labels).
- To accomplish that, we need to extract the “language grammar” of the gamma ray log.
The Gamma Ray Log Data Set

- A sequence of 6,150 data points were collected from a deepwater reservoir.
- Each data point was taken at a half foot interval between 4,200 and 7,200 feet under the earth surface (deepwater).
- A stratigrapher has examined the data and assigned 50 depositional labels at different depth level.
Gamma Ray Log Data Segmentation

- Normalize the data: gr → vsh
- Segment the data:
  - Start with one data point in each segment.
  - Step by step, neighboring segments are combined to reduce the number of segments.
  - The segments whose merging will lead to the least increase of “error” are combined.
  - The process stops when the sum of total “error” and the number of segment starts increasing.
  - The average of the data with each segment is used to represent the value of the segment.

\[ vsh = \bar{s}_1, \bar{s}_2 \ldots \bar{s}_n \]
Each $s_i$ is mapped into one of the 10 symbols: a, ab, ba, b, bc, cb, c, cd, dc, d, according to the following fuzzy membership functions.
After adjusting the division point to align with the position of the 50 depositional labels, the 6,150 data points are represented by 82 symbols.
Recall that stratigraphic interpretation is a process of gamma ray log trend identification.

- Blocky: Channel-axis (A)
- Irregular: Over-bank (OB)

In addition to gamma ray input, the stratigrapher considers other factors, such as the thickness of each segment and the degree of variation of neighboring segments, to decide labels.

In order to capture the interpretation model, this information is calculated for each depositional unit.

<table>
<thead>
<tr>
<th>attribute</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>symbol thickness</td>
<td>The total thickness of each of the 10 symbols</td>
</tr>
<tr>
<td>total thickness</td>
<td>The thickness of the unit</td>
</tr>
<tr>
<td>symbol%</td>
<td>The % of each of the 10 symbols</td>
</tr>
<tr>
<td>symbol max thickness</td>
<td>The max thickness of each of the 10 symbols</td>
</tr>
<tr>
<td>no of segment</td>
<td>The no of segments</td>
</tr>
<tr>
<td>variation</td>
<td>Average distance of the neighboring symbols in the unit</td>
</tr>
</tbody>
</table>
The calculated attribute values were used to train 5 classifiers.
The data contain 50 depositional units: 
- A: 4; OA: 9; M:14; OB:19; MTC:4.
Co-evolve a team of 5 classifiers that gives the overall best result.
If (OA-rule is evaluated to be True) then OA
else if (A-rule is evaluated to be True) then A
else if (MTC-rule is evaluated to be True) then MC
else if (OB-rule is evaluated to be True) then MTC
else if (OB-rule is evaluated to be True) then OB
else M
• Mass sandstone, high GR, low vsh value (symbol a), low variation
Finite State Transducer Representation

- **Two tables:**
  - **Next State Table:** gives the next state, based on the current state and the input symbol.
  - **Output Label Table:** gives the name of the classifier that is used to decide the output depositional label, based on the current state and the input symbol.

<table>
<thead>
<tr>
<th>input</th>
<th>a</th>
<th>ab</th>
<th>ba</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_0</td>
<td>S_8</td>
<td>S_2</td>
<td>S_19</td>
<td>S_18</td>
</tr>
<tr>
<td>S_1</td>
<td>S_9</td>
<td>S_17</td>
<td>S_4</td>
<td>S_10</td>
</tr>
<tr>
<td>S_2</td>
<td>S_9</td>
<td>S_18</td>
<td>S_1</td>
<td>S_3</td>
</tr>
<tr>
<td>S_19</td>
<td>S_13</td>
<td>S_2</td>
<td>S_15</td>
<td>S_0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>input</th>
<th>a</th>
<th>ab</th>
<th>ba</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_0</td>
<td>OA</td>
<td>OB</td>
<td>OB</td>
<td>OB</td>
</tr>
<tr>
<td>S_1</td>
<td>OA</td>
<td>MTC</td>
<td>OB</td>
<td>M</td>
</tr>
<tr>
<td>S_2</td>
<td>OB</td>
<td>OA</td>
<td>MTC</td>
<td>A</td>
</tr>
<tr>
<td>S_19</td>
<td>A</td>
<td>MTC</td>
<td>A</td>
<td>MTC</td>
</tr>
</tbody>
</table>
**Operation of a Finite State Transducer**

- **Inputs to the FST:**
  - a sequence of vsh symbols with its thickness
  - 5 classifiers.
- **Outputs of the FST:**
  - a sequence of depositional labels.
- When a vsh symbol is processed, the output can be either a depositional label or a nil.
### Experimental Results

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tournament selection</td>
<td>Size 2</td>
</tr>
<tr>
<td>Population size</td>
<td>20</td>
</tr>
<tr>
<td>Elitism</td>
<td>Size 1</td>
</tr>
<tr>
<td>FST no. of states</td>
<td>20</td>
</tr>
<tr>
<td>Mutation rate</td>
<td>2%</td>
</tr>
</tbody>
</table>

- 7 mis-classifications out of the 82 symbols.
  - \( M \rightarrow OA \): 2
  - \( A \rightarrow OA \): 1
  - \( OB \rightarrow \text{nil} \): 2, combined to the next \( M \) label.
  - \( OB \rightarrow M \): 2
Concluding Remarks

• Automating the interpretation of deepwater reservoir depositional environments can help in reducing stratigraphers workload and produce more consistent results.
• The developed methodology and workflow generate interpretation results that are close to the results produced by the stratigrapher.
• Future work:
  – Acquire new data sets to test the generality and scalability of the developed method.
  – Help stratigraphers to understand the developed process.
  – Apply the process to interpret higher-level components in the stratigraphical hierarchical framework.