The Permian Basin covers a huge area in western Texas and southeastern New Mexico:

- 52 counties
- 75,000 square miles
  - (48 million acres)
- The Permian Basin is split into 2 main sub-basins
  - Midland Basin
  - Delaware Basin

Fig. 1. Map of Permian Basin Structural Setting. Murchison Oil and Gas. 2010. Web. 9 Oct 2015.
23 prospective formations with up to 25,000 ft of multiple, stacked, petroleum systems

Extensive drilling, coring and geological studies since 1920s

> 1,000 operators

> 500k wells

Cumulative production
- > 29 BBO
- > 75 Tcf of gas

Fig. 3. Map of Sub-Basins in the Permian. Shale Experts. 2015.
Problem and Challenges

- Operator reported producing formation not specific enough
- Analyzing individual well log data time-intensive to capture
- Visualizing production data on 2D map does not offer perspective of stacked play
- Integrating large volumes of data

Fig. 5. Integrated 3D model displaying data from different disciplines including well deviation surveys, a seismic cross section and 3D volume, and production information displayed in the pie charts. Dynamic Graphics. 2015.
Goals and Objectives

• Develop workflow to improve efficiency of regional basin analysis
• Interpolate well log data to sub-delineate formations into contiguous producing horizons
• Specify completion and production from productive horizons
• Create surfaces for petrophysical parameters
• Interpolate well log metrics from control locations to wells that have not been interpreted

Fig. 6. Map showing stacked formations. *Midland Basin: Multi-stacked Horizontal Targets*. Oil & Gas Journal. 2015.
Methodology: Mapping Formations & Well Log Attributes

- Obtain text file of geologist’s interpreted data
  - Unique identifier (API)
  - Coordinates
  - Horizon name
  - Total vertical depth subsea (TVDSS)
  - Metrics from raw well log data
    - Gamma ray (API units)
      - measures the radioactivity of rocks to determine the amount of shale in a formation
    - Resistivity (ohm⋅m)
      - measures electrical resistivity for formation evaluation
    - Neutron porosity (porosity units)
      - measures the hydrogen content in a formation
    - Bulk density (g/cm³)
      - used in conjunction with neutron density to determine porosity and identify hydrocarbons

Fig. 7. Interpreted well log. Matt Boyce, PhD. 2013. Southwestern Energy.
Methodology: Exploratory Spatial Data Analysis

• Get to know your data

Hello
my name is

Data

\( f_X(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \)

I’m perfectly normal!

YOUR SAMPLE SIZES ARE SMALL
YOUR STANDARD DEVIATIONS ARE HIGH
YOUR CONCLUSION MEANS NOTHING
AND YOU SHOULD FEEL BAD

Indicators of a normal distribution
• Bell-shaped curve
• Mean & median close to the same value
• Skewness close to 0
• Kurtosis close to 3

8
Methodology: Interpolation Methods

• Deterministic Methods
  • Use defined algorithms that take into account the distance between a known location and a queried location
    • Natural neighbors
    • Inverse distance weighting (IDW)
    • Spline
    • Trend

• Probabilistic Methods
  • Use a statistical approach to quantify the uncertainty associated with the prediction
    • Kriging
      • Simple
      • Ordinary
      • Universal
      • Empirical Bayesian kriging

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computationally fast</td>
<td>Does not account for spatial relationship of data</td>
</tr>
<tr>
<td>Easy to run</td>
<td>Produces boundary bias</td>
</tr>
<tr>
<td>Available in most software packages</td>
<td>Creates bull’s eye effect</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantages</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Accounts for spatial relationship of data</td>
<td>Slower to run than deterministic methods</td>
</tr>
<tr>
<td>Produces more accurate results than deterministic methods</td>
<td>Parameters less intuitive than deterministic methods</td>
</tr>
<tr>
<td>Best linear unbiased prediction (BLUP)</td>
<td>Must investigate dataset before modelling</td>
</tr>
</tbody>
</table>
Methodology: Kriging – Background

**Kriging**
- Kriging uses a Gaussian statistical model to optimize spatial prediction
- Used in meteorology, mining, forestry, hydrology, soil sciences, geology, public health, petroleum engineering

**Origins**
- Danie Gerhardus Krige – South African Mining Engineer (1951)
- Georges Matheron – French mathematician and geologist, formalized Krige’s work and founded mathematical morphology

**Other Contributors**
- Mercer and Hall (1911)
- Youden and Mehlich (1937)
- Kolmogorov (1941)
- Lev Gandin (1959)
- Matérn (1960)
Methodology: Kriging – Benefits and Limitations

**Benefits**
- Accounts for distance and direction of the data
- Optimal predictor
- Best unbiased linear predictor (BLUP)
- Generally have smaller error than other interpolation models
- Ability to filter out measurement errors
- Uses a semivariogram to quantify spatial dependence in the data
- Ability to generate prediction, quantile, and standard error maps
- Includes cross-validation

**Limitations**
- Assumes the semivariogram is always correct when applying function to the data
- If data does not have a normal distribution the error associated with the prediction is underestimated
Methodology: Empirical Bayesian Kriging (EBK)

- Accounts for uncertainty introduced in the semivariogram
- Uses “intrinsic random functions” that inherently correct for trends in the data
- Able to remove local trend in dataset
- Can be used to interpolate non-stationary data for large areas
- Generally more accurate than other kriging for small datasets

- Many methods to model the semivariogram
  - Power, linear, exponential, thin plate spline, whittle, and K-Bessel
  - Different models impact the model’s flexibility, accuracy, and calculation time

Fig. 9. Output surfaces from geostatistical analyst. Esri Japan, 2016.
Methodology: EBK – Parameters & Glorious Semivariograms

- Unique distribution of semivariograms for each point in dataset
- Median distribution indicated with dark red line
- Percentiles shown with dashed red lines
Methodology: EBK – Cross Validation

• View error associated with each predicted point
• Optimize results to obtain most precise grid
• “Cross-linking” enabled

Prediction errors for dataset should have:
• Mean Standardized Error near 0
• Root-Mean-Square Stnd Error near 1
• Average Standard Error as small as possible

* RMS near 1 is key to a stable model
Results: EBK – Contiguous Prediction & Standard Error Maps

AOI covers 21,075,775 acres
Results – Well Horizon Classification

State Data – Formation 1

Internal Sub-delineation – Formation 1d

Internal Horizons – Formation 1a-d
Results – Well Log Attribute Classification

- Interpolated grids for well log attributes for each formation
- Extracted petrophysical well log attributes from grids and applied to all wells in the horizon

Well control points with interpreted petrophysical property are shown symbolized from a low-to-high value

Grids are created from control points for petrophysical parameter using EBK

Wells producing from the same horizon that have not been evaluated are shown in grey

Extract value from EBK grid to State’s well dataset; the values for each of the petrophysical properties was extracted to the well bore
• EBK interpolated grids for each horizon (SSTVD)

Fig. 9. Screenshot of geologic horizon shown in 2D view in ArcMap (left) and in 3D view in Transform software (right). Horizon generated using EBK process in GIS. Transform screenshot provided by Cullen Hogan, January 6, 2016.
• Convert Esri GA Layers to raster grid format for use in other software

• Provide geophysicist grids for use in 3D model

• Integrate data

• Visualize and classify producing horizons

Fig. 10. Screenshot of structural model in JewelSuite software displaying wells intersecting target formations. Screenshot provided by Cullen Hogan, February 4, 2016.
Summary
A special thanks to the team at Southwestern Energy

Southwestern Energy’s Permian Basin Team

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Demola Soyinka – Staff Geologist
Jeremy Andrews - Geologist
Kyle Magrini – Staff Reservoir Engineer
Matt Boyce, PhD – Staff Geologist

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Questions?