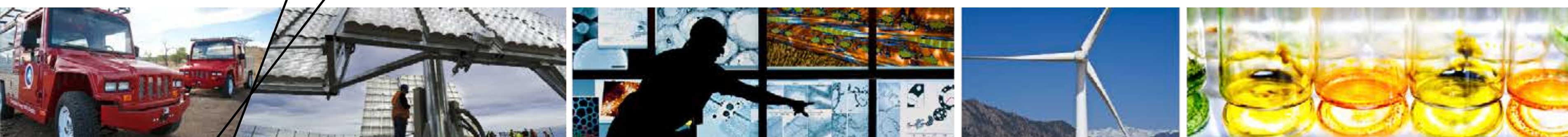
NATIONAL RENEWABLE ENERGY LABORATORY

Recoverable Resource Estimate of Identified Onshore Geopressured Geothermal Energy in Texas and Louisiana



AAPG 2012 Annual Convention and Exhibition

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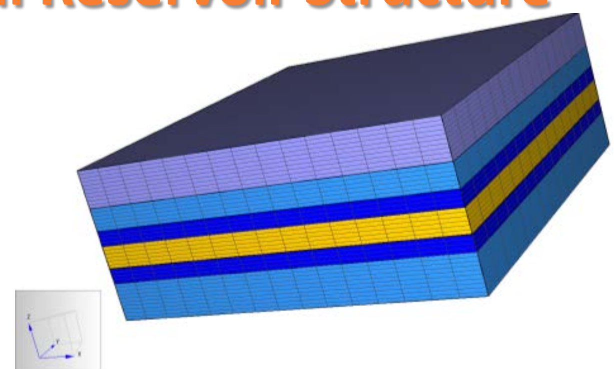
Geopressured Geothermal Resource

- **Geopressured Geothermal**
  - Reservoirs characterized by pore fluids under high confining pressures and high temperatures with correspondingly large quantities of dissolved methane
  - Soft geopressure: Hydrostatic to 15.83 kPa/m
  - **Hard geopressure: 15.83– 22.61 kPa/m (lithostatic pressure gradient)**
- **Common Geopressured Geothermal Reservoir Structure**
  - Upper thick low permeability shale
  - Thin sandstone layer
  - Lower thick low permeability shale



- **Three Potential Sources of Energy**
  - Thermal energy (Temperature > 100°C – geothermal electricity generation)
  - Chemical energy (natural gas)
  - Mechanical energy (pressurized fluid)

Introduction

Motivation

- **The Gulf Coast geopressured geothermal resource is the most extensive of any region in the United States**

Goals

- **Estimate the geopressured geothermal resource in the Gulf Coast for combined production of natural gas and electricity**
  - Total heat in place and recoverable thermal energy
  - Total geothermal electricity generation potential
  - Total natural gas that could be recovered with geothermal fluid
- **Fully utilize previously published datasets**
- **Incorporate results from reservoir modeling of geopressured geothermal reservoirs in the estimate**

Background and Methodology

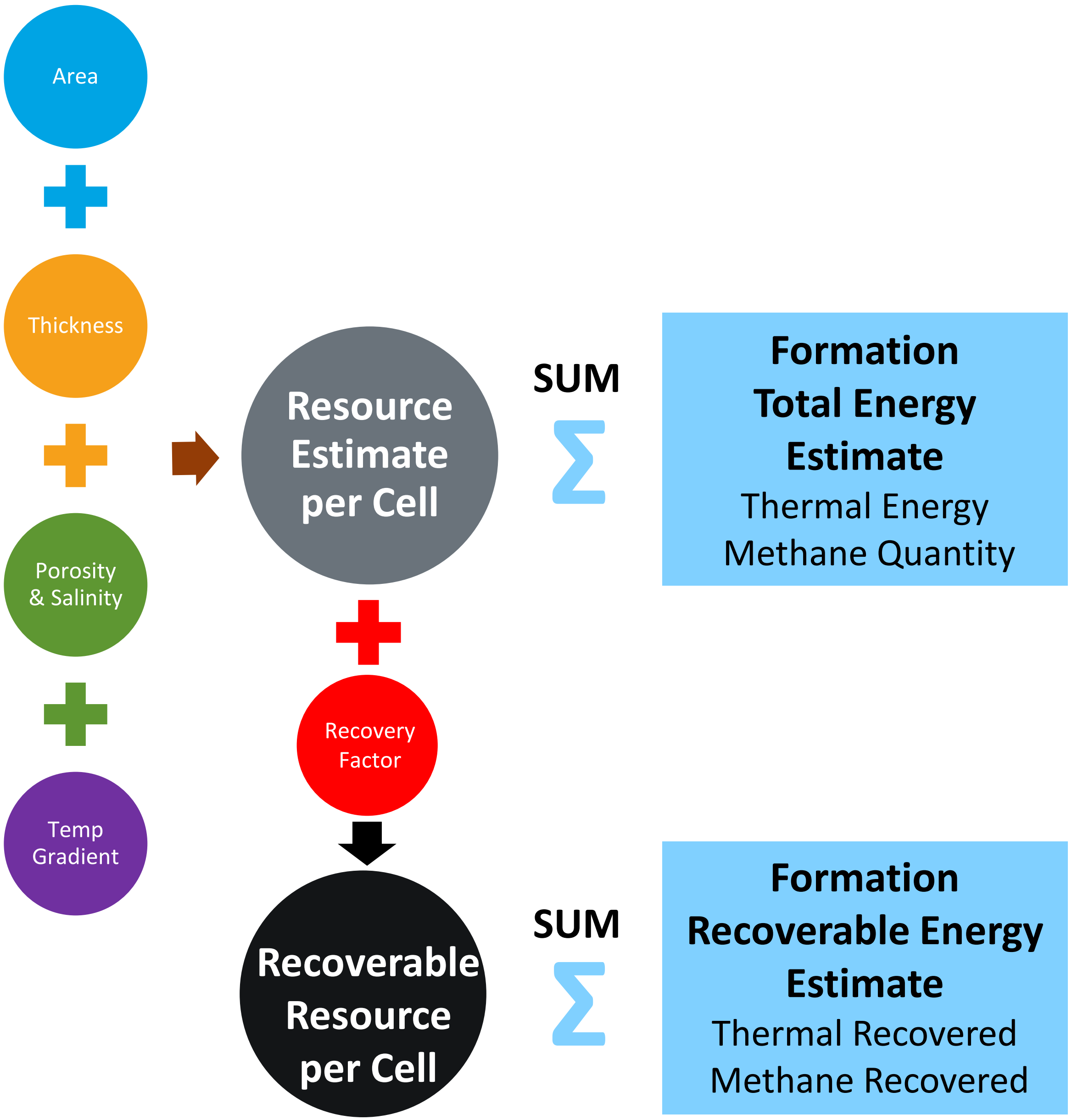
1. **Determine geopressured geothermal resource regions within Texas and Louisiana**
   - Five formations identified within Texas: Lower Wilcox, Lower Claiborne, Upper Claiborne, Vicksburg-Jackson, and Lower Frio
2. **Collect all relevant data on five formations in Texas and geopressured geothermal region in Louisiana**
   - Sand and shale thickness, depth to geopressure, porosity, and temperature
3. **Complete resource estimate using spatial analysis of Texas formations and Louisiana**
   - Populate a grid of cells ($A = 1\ km^2$) region with data
   - Estimate geopressured geothermal resource for each grid cell

Background

- **Previous work includes detailed multiphase flow reservoir modeling of geopressured geothermal fairways in the Frio and Wilcox formations (Esposito and Augustine 2011)**
- **Reservoir modeling provided insight on geothermal brine and natural gas flow rate profiles over a long-term time frame, reservoir pressure and temperature changes with time, and potential recovery factors**

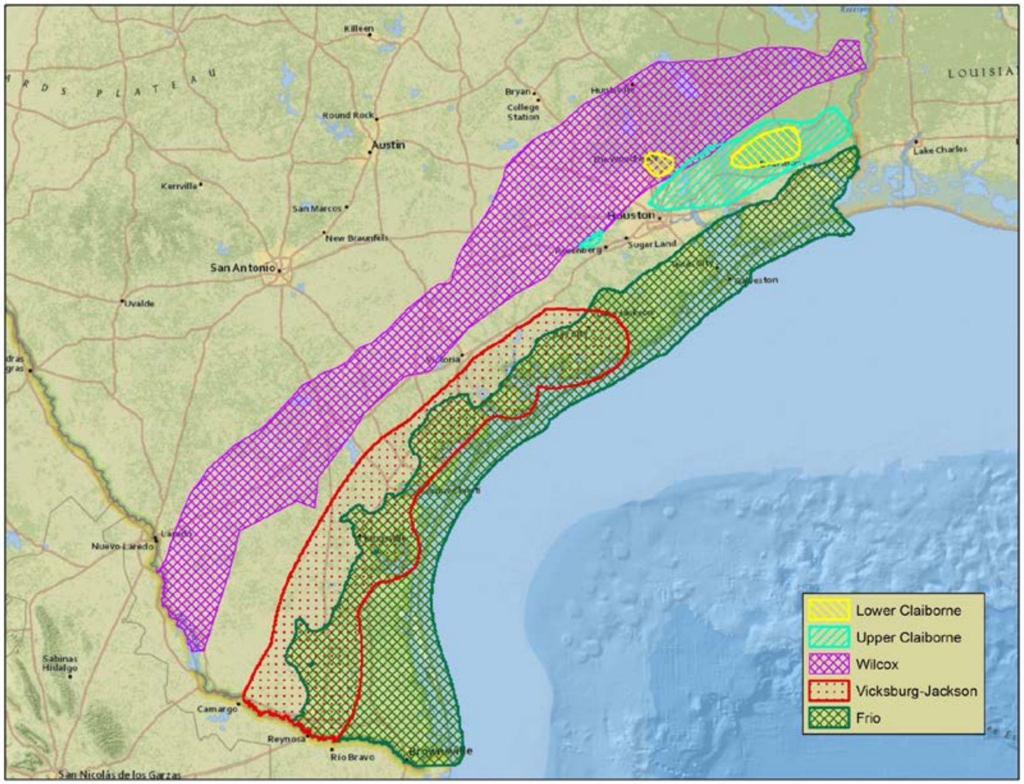
Geopressured Geothermal Resource Estimate

The total resource and the recoverable energy are calculated for each cell within the geopressured area of the formation and then summed over the entire formation to obtain the formation estimates.



Texas Geopressured Formation Areas

Multiple formations are present at the same location but at different depths

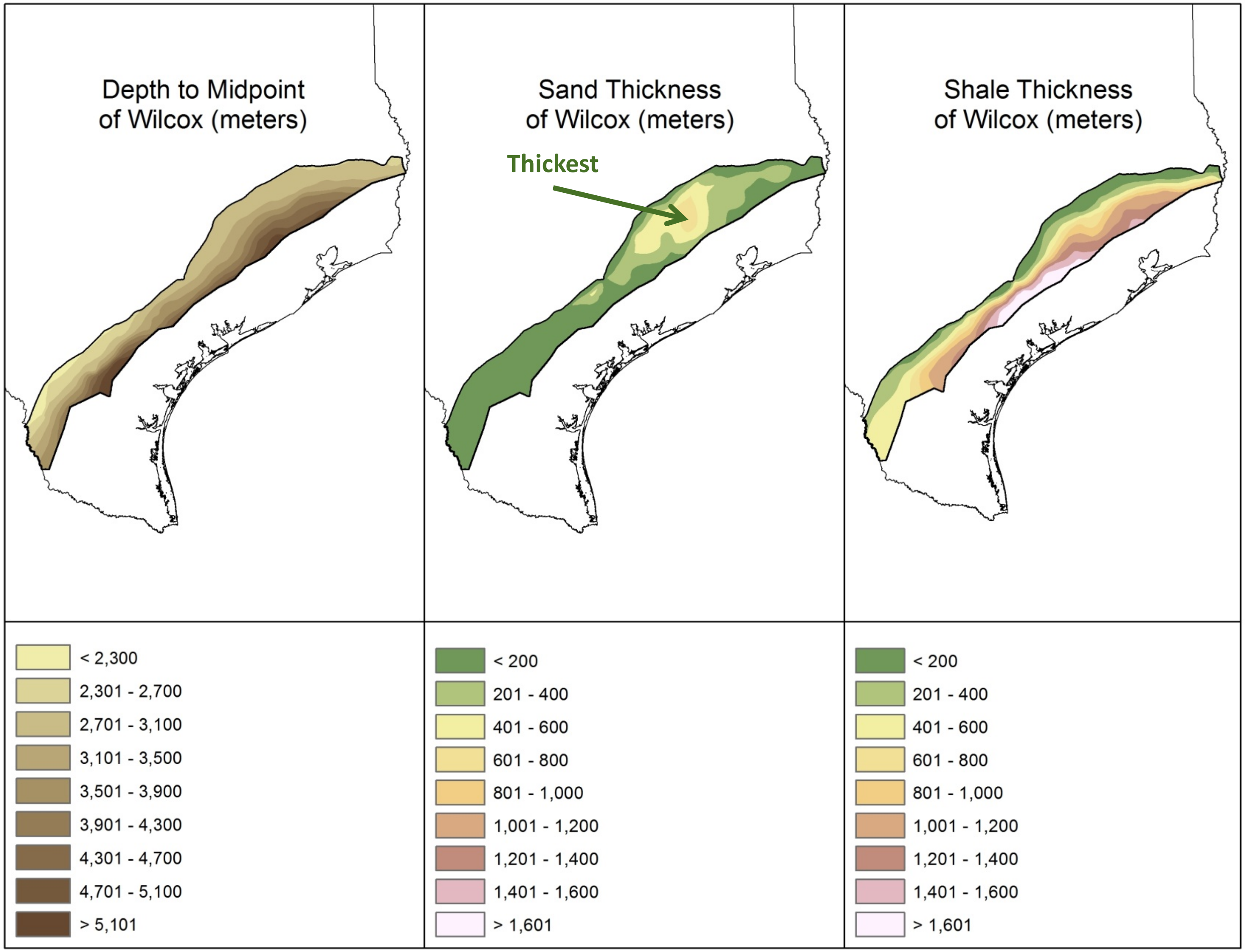


Spatial Analysis Criteria

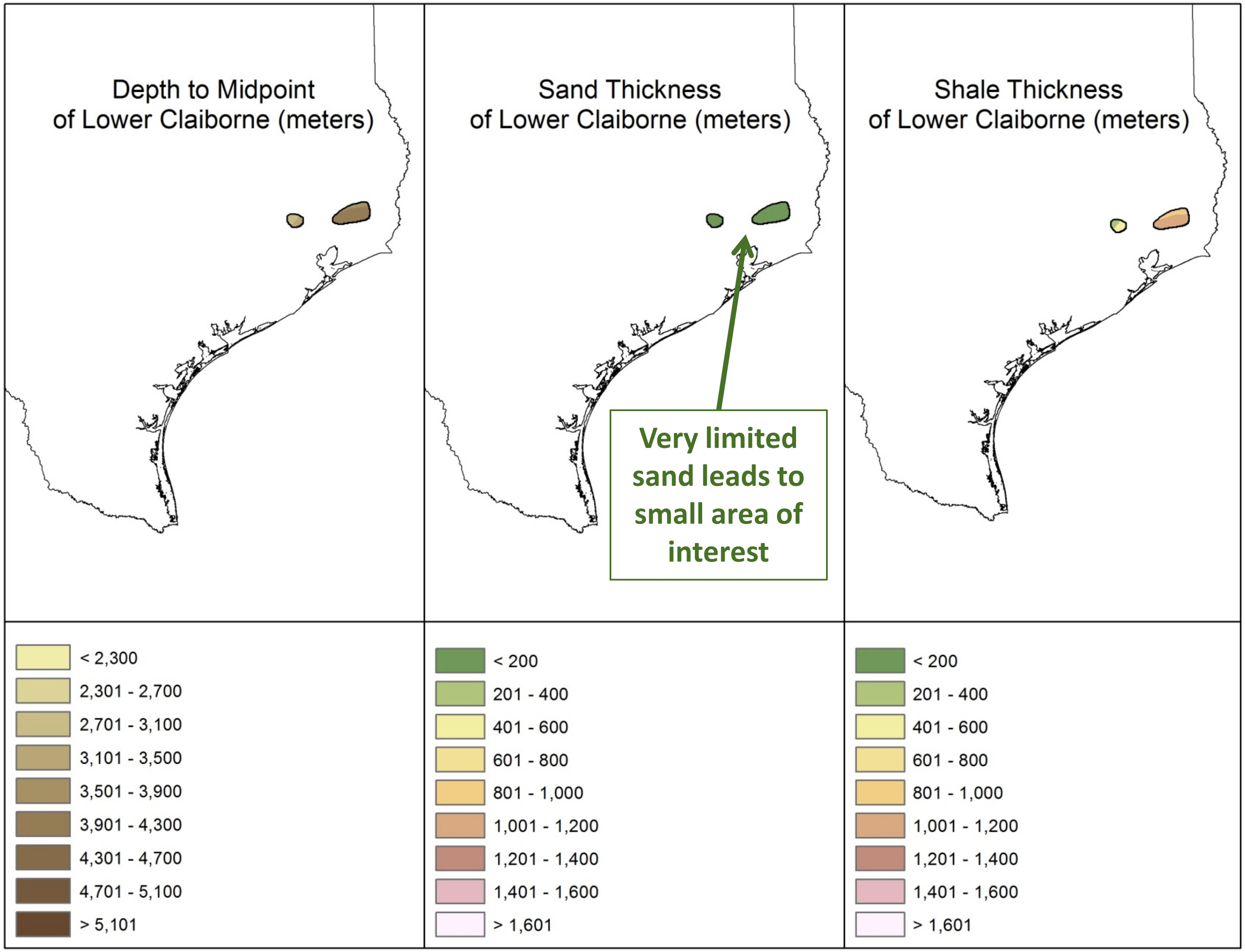
1. Total sand thickness must be greater than 30 m
2. A pressure gradient of 11.3 kPa/m falls above or within sandstone
3. Porosity data is available
4. Some regions in formation have temperatures above 100°C

Formation	Geopressured Area (km^2)
Lower Wilcox	42,534
Lower Claiborne	1,439
Upper Claiborne	5,785
Vicksburg-Jackson	26,821
Lower Frio	42,334

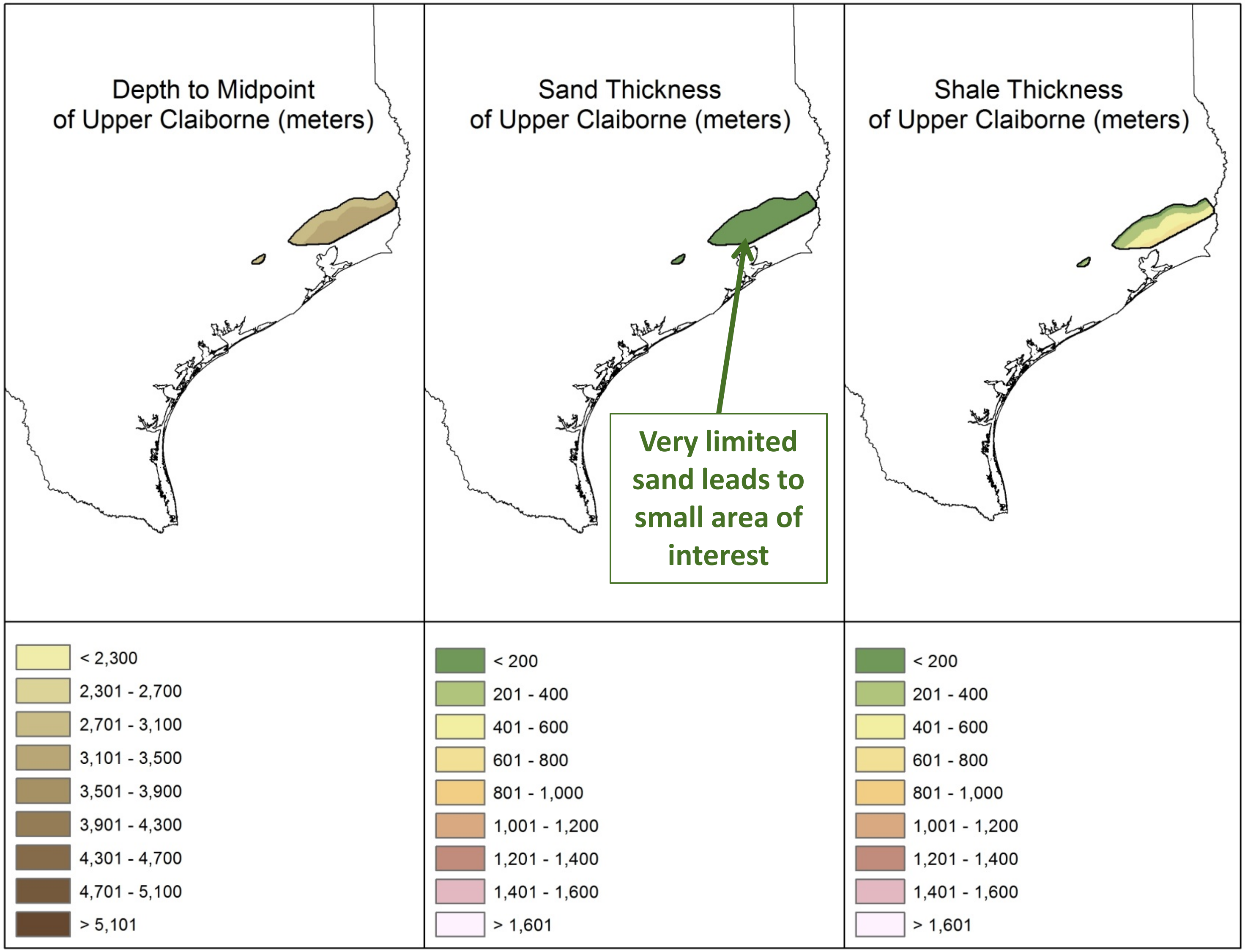
Lower Wilcox Geopressured Area



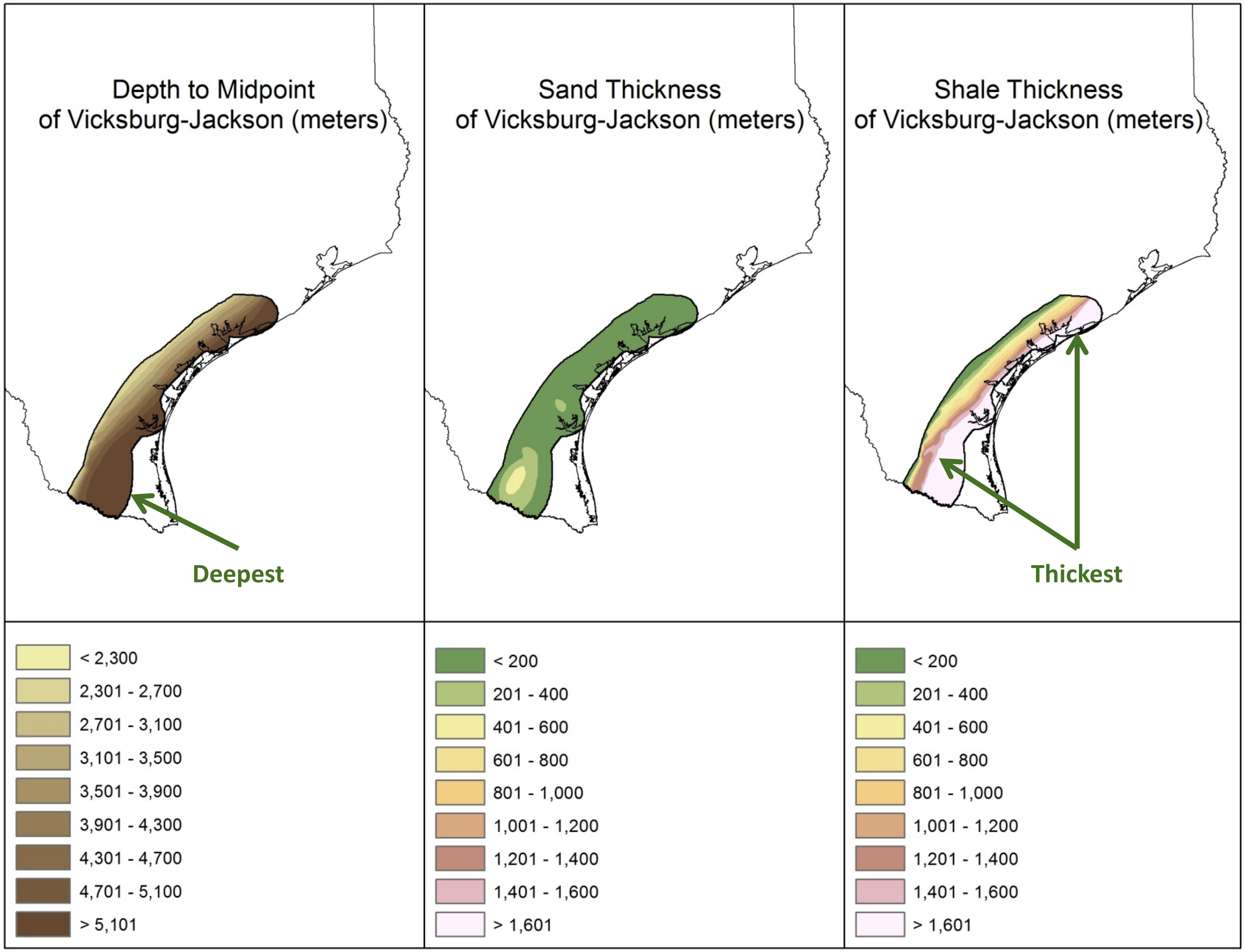
Lower Claiborne Geopressured Area



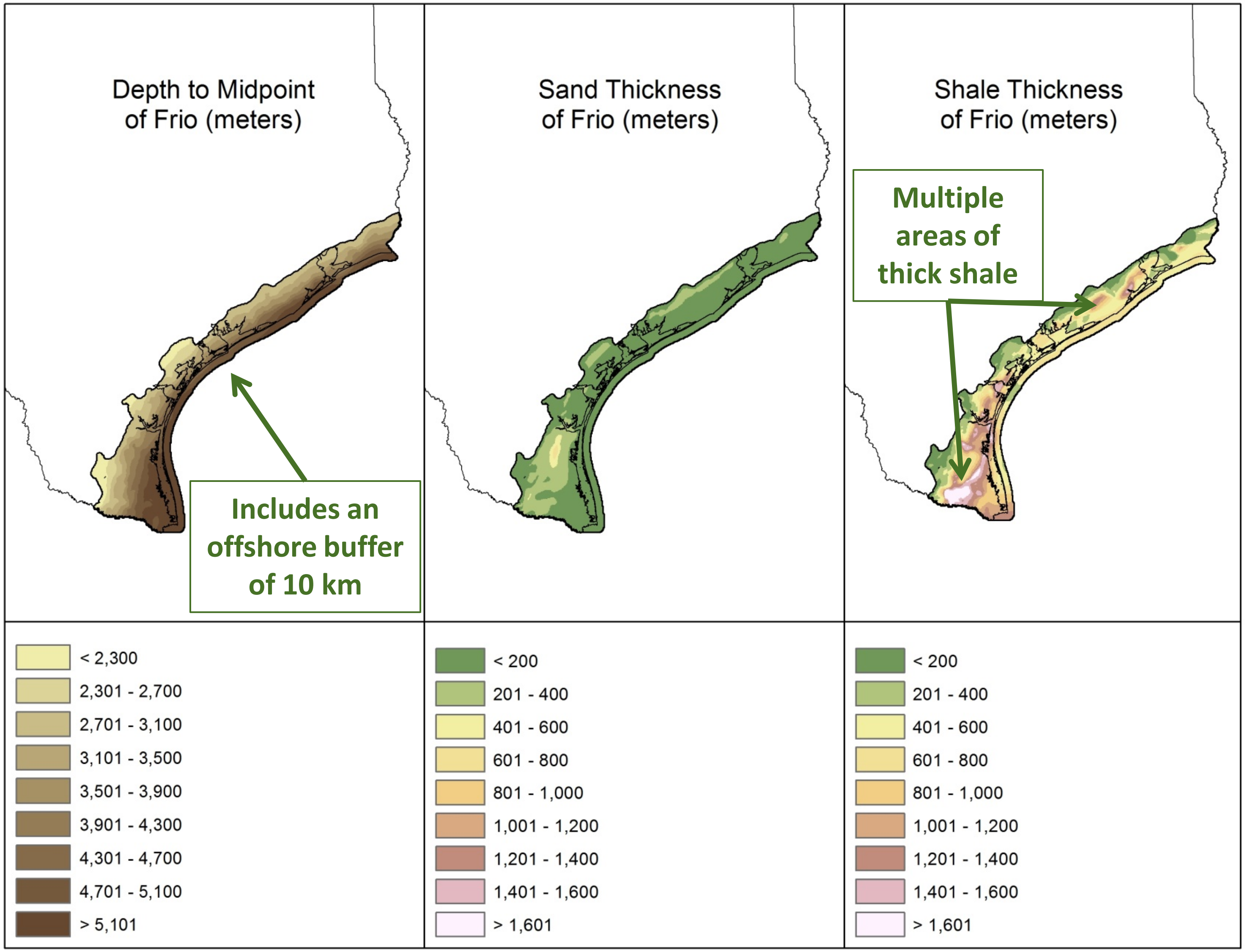
Upper Claiborne Geopressured Area



Vicksburg-Jackson Geopressured Area



Lower Frio Geopressured Area



Texas Geopressured Formation Summary

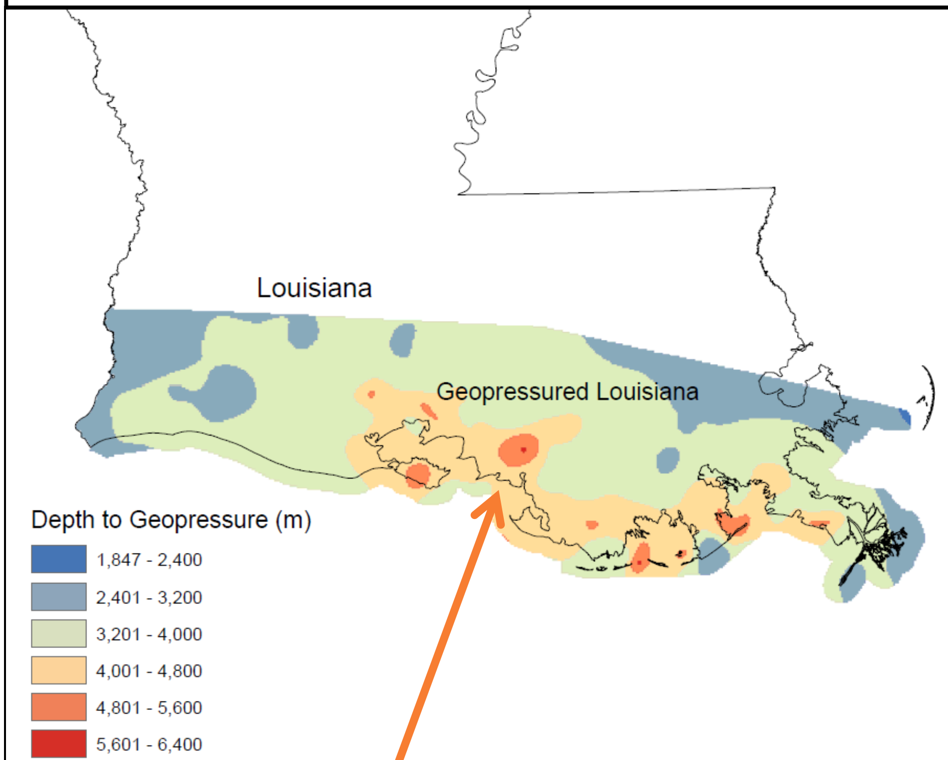
Formation		Lower Wilcox	Lower Claiborne	Upper Claiborne	Vicksburg Jackson	Lower Frio
Average Sand Thickness		**185**	8	48	114	123
Average Shale Thickness		725	922	411	1,286	681
Midpoint Depth	Min	1,904	**2,795**	2,732	2,427	1,814
	Max	5,571	4,217	3,486	**6,278**	5,712
	Avg	3,436	3,833	3,142	**4,524**	3,989
Average Porosity		11.3	17.7	**21.3**	13.5	12.9
Total Area (km^2)		46,944	28,783	17,741	28,567	**117,223**
Area of Interest (km^2)		**42,534**	1,439	5,785	26,821	42,334
Area of Interest to Total Area		0.91	0.05	0.33	**0.94**	0.36

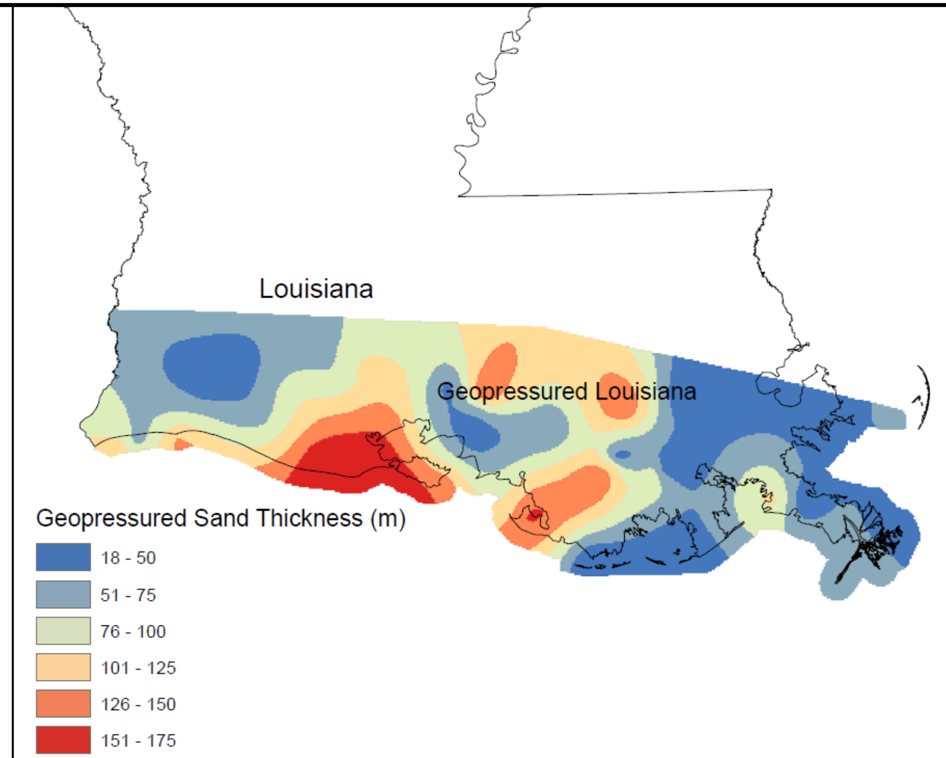
Maximum (boxed)

Louisiana Geopressured Area

Data on any shale present in the geopressured region was not available. In this analysis, the formation only consisted of sandstone.

Depth to Geopressure (meters)	Geopressured Sand Thickness (meters)





Greatest depth to geopressure near coast

Temperature Estimation at Reservoir Midpoint

- **Input Data:**
  - AAPG bottom hole temperature (BHT) measurements
    - More than 27,000 data points for United States
  - Correct BHT using the Kehle correction up to 3,930 m

$$\Delta T = -1.73 \times 10^{-10} Z^3 - 1.28 \times 10^{-7} Z^2 + 7.97 \times 10^{-3} Z - 0.565 \text{ [°C]}$$

  - After 3,930 m use linear equation (Blackwell et al. 2010)

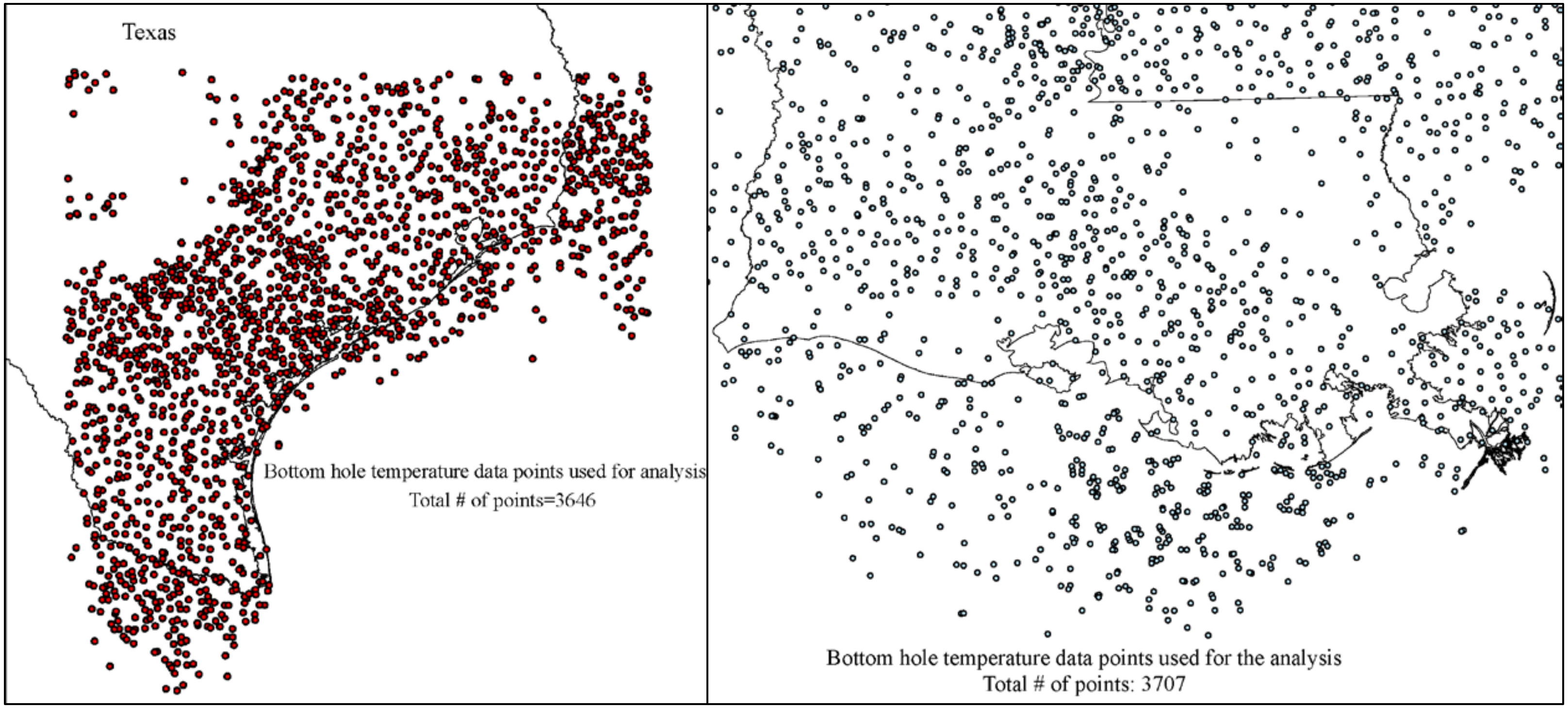
$$\Delta T = 19 + 3.28 \times 10^{-4} * (Z - 3{,}930) \text{ [°C]}$$

- **Temperature Interpolation (MATLAB):**
  - Fluid temperature is calculated at the grid cell midpoint

1. Delaunay triangulation of the scattered data locations
   - Input: x, y, depth (z), and corrected BHT
2. Linear interpolation of temperature to midpoint of grid cell
   - Temp (x, y, z) ⟶ Gridded: x, y, midpoint (z) points

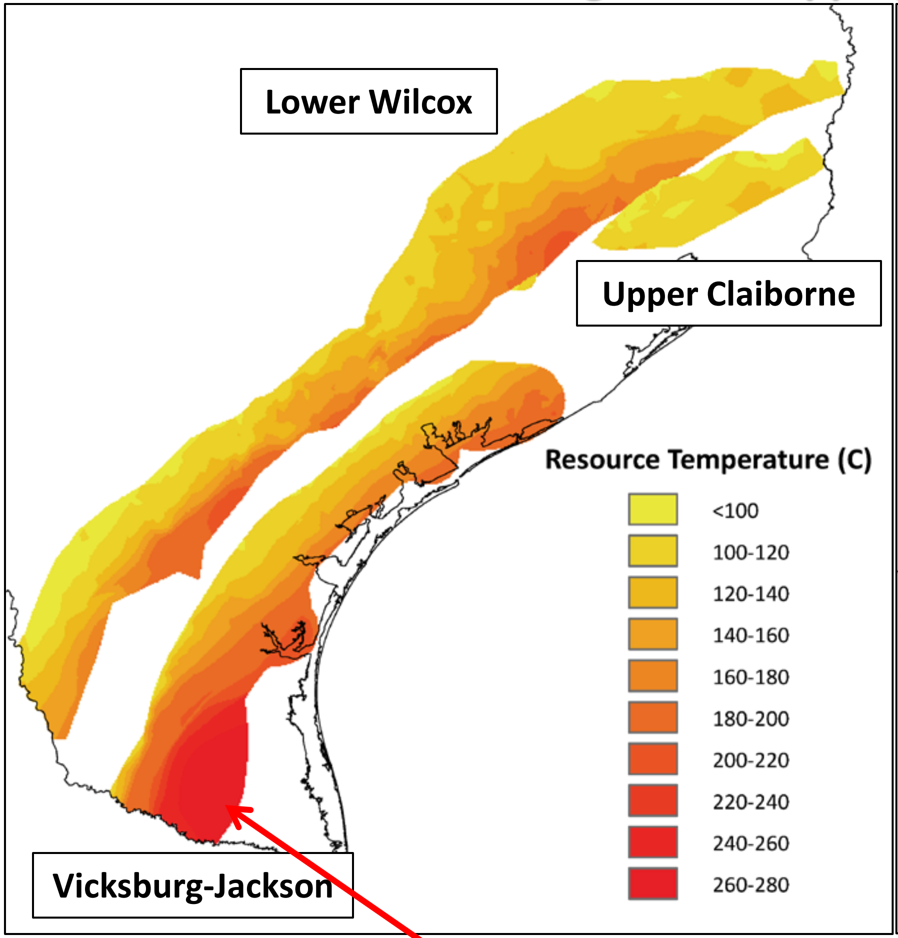
Temperature Data

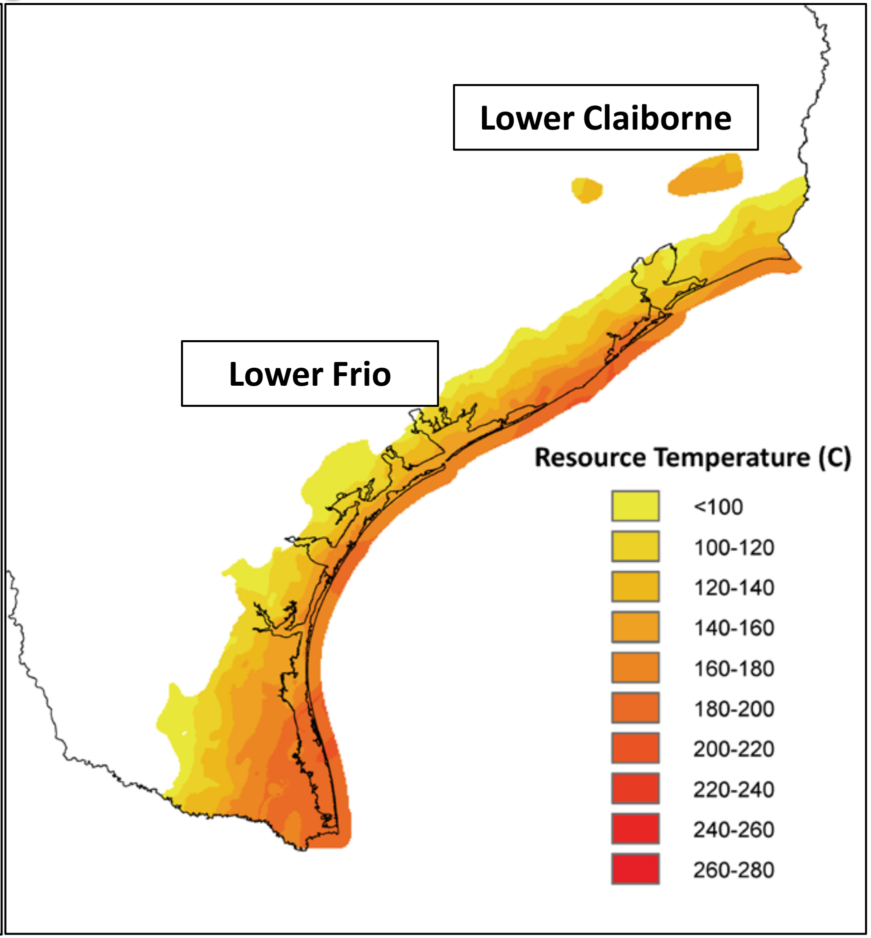
Location of data points from AAPG BHT database selected for analysis



Midpoint Temperature Estimate - Texas

The midpoint temperature in all five formations increases towards the coast due to the significant dipping in each formation.





Maximum temperature of 273°C occurs in southern Vicksburg Jackson

Resource Estimate Assumptions

- Sand and shale thickness is uniform throughout the grid cell area of 1 km^2
- Sandstone is located in center of formation and bounded by upper and lower shale
- Pressure gradient at midpoint depth is 15.83 kPa/m

Heat Capacity, Enthalpy, and Entropy calculations:

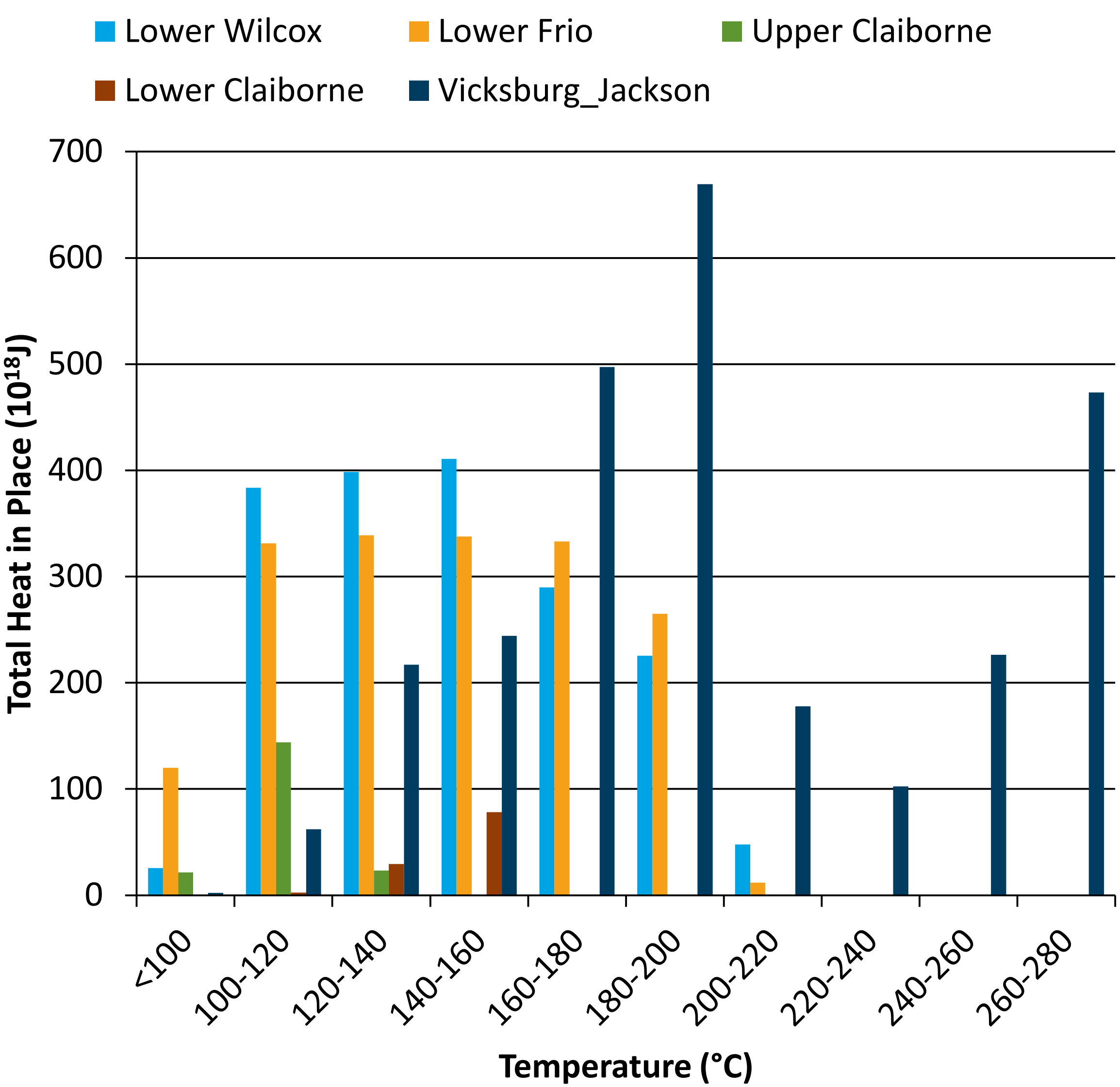
6th order polynomials in terms of temperature

Fluid Density at Reservoir Conditions (ρ_R):

$$\rho_R = \rho_0 (1 - (P_R - P_0)/E)/(1 + \beta(T_R - T_0)) \ [kg/m^3]$$

- E : bulk modulus for water (2.1 x 10^9 Pa)
- β : volumetric temperature expansion coefficient (0.0004 $m^3/m^3 \,^oC$)
- P_0 : reference pressure | P_R : reservoir pressure
- T_0 : reference temperature | T_R = reservoir temperature
- ρ_0 : reference fluid density

Texas: Total Heat in Place (Sandstone and Shale)



Heat in Place Method

1. Total mass (m_T):

$$m_T = \varphi \cdot \rho \cdot A \cdot (z_{sand} + z_{shale})$$

2. Heat in place (J_T):

$$J_T = m_T \cdot c_P \cdot (T_R - T_0)$$

with $T_0 = 25\ °C$

Formation	Total (J)
Vicksburg-Jackson	2.67E+21
Lower Wilcox	1.78E+21
Lower Frio	1.74E+21
Upper Claiborne	1.89E+20
Lower Claiborne	1.10E+20

Total Recoverable Energy Calculations

1. Recoverable Mass (m_{wh})

$$m_{wh} = RF \cdot V_T \cdot \varphi \cdot \rho$$

- RF : recovery factor
- V_T : total volume
- φ : porosity
- ρ : fluid density

2. Exergy (E)

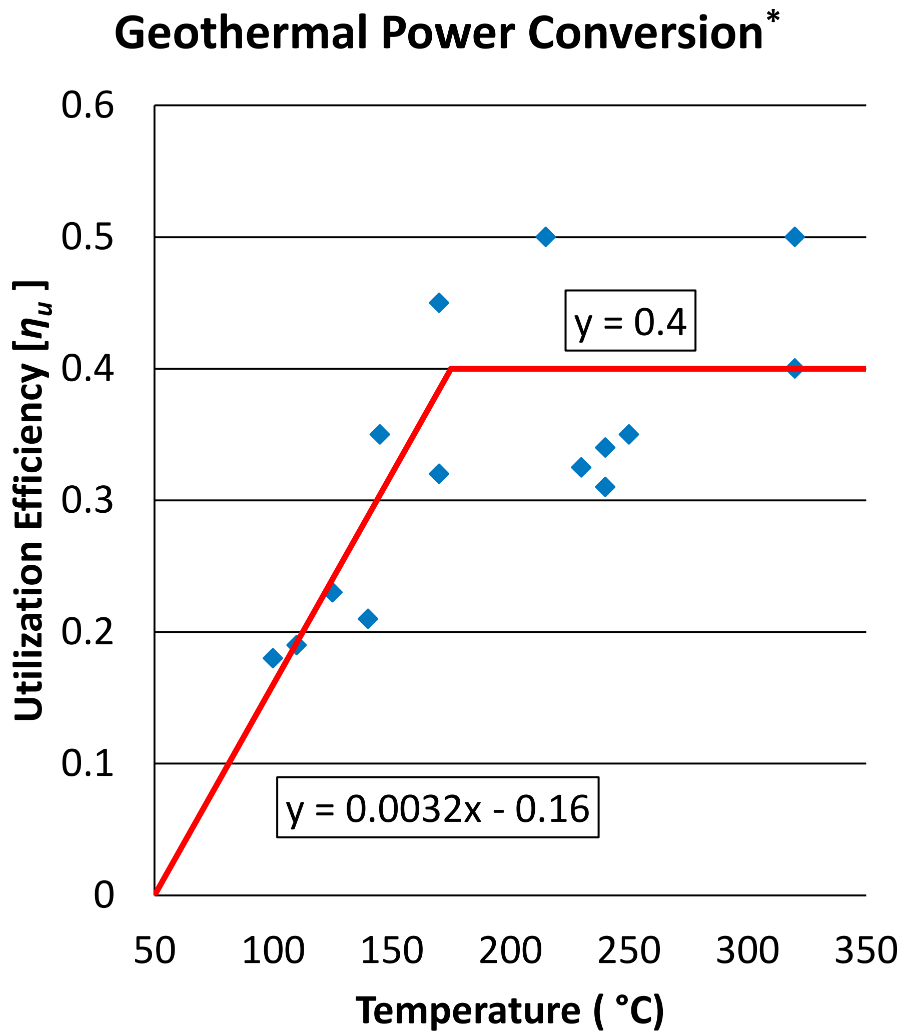
$$E = m_{wh}[h_{wh} - h_0 - T_0(s_{wh} - s_0)]$$

- h_{wh} : fluid enthalpy
- h_0 : reference enthalpy
- T_0 : reference temperature
- s_{wh} : fluid entropy
- s_0 : reference entropy

3. Electricity Generation Potential (W_e)

$$W_e = E \cdot \eta_u$$

- η_u : utilization efficiency



*Williams et al. 2008

Texas: Recovery Factors from Reservoir Modeling

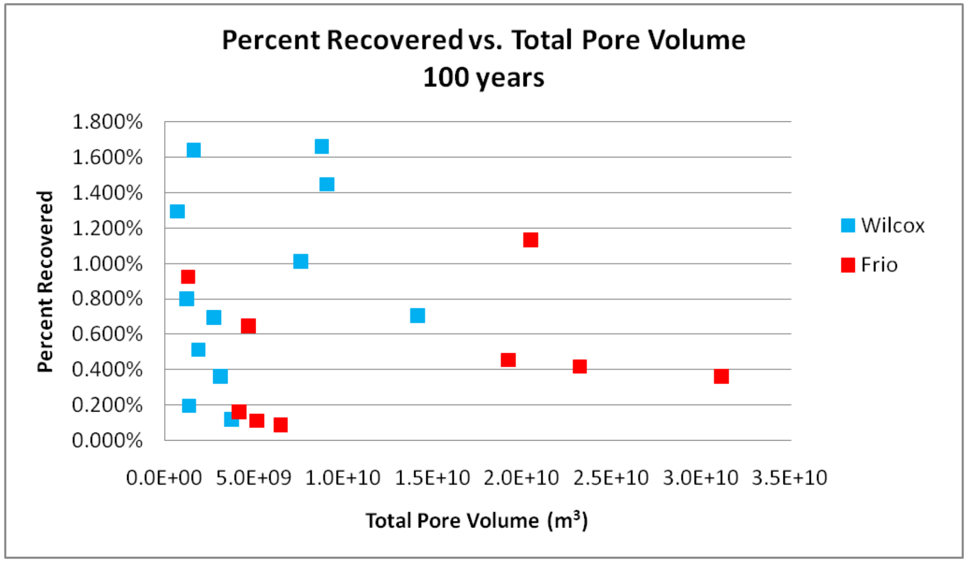
Recoverability Factor (RF) = Volume Recovered/Total Pore Volume

Frio Recoverability Factors:

- **Data were collected for five fairways**
  - Developed 9 unique reservoir models
- **Recovery factor was calculated:**
  - 20-year average: 0.325%
  - RF 100-year average: 0.486%
- ***Frio 20-year average RF of 0.325% was also applied to Vicksburg Jackson***

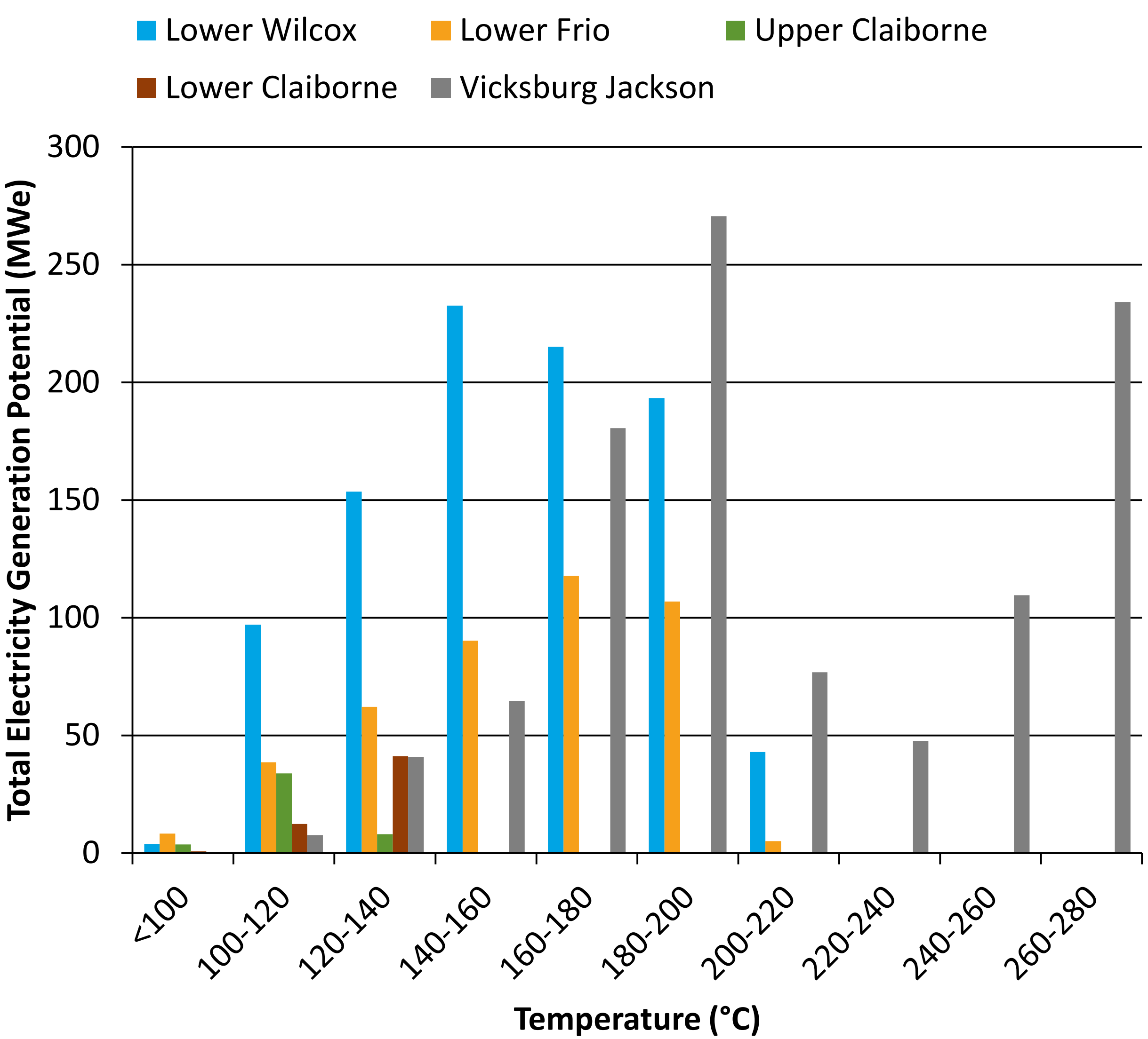
Wilcox Recoverability Factors:

- **Data were collected for six fairways**
  - Developed 12 unique reservoir models
- **Recovery factor was calculated:**
  - 20-year average: 0.685%
  - 100-year average: 0.870%
- ***Wilcox 20-year average RF of 0.685% was also applied to Lower and Upper Claiborne***



Source: Esposito and Augustine 2011

Texas: Electricity Generation Potential



Formation	Total Elecricity (MWe)
Vicksburg-Jackson	1,032
Lower Wilcox	939
Lower Frio	429
Lower Claiborne	54
Upper Claiborne	46

Louisiana: Heat in Place (Only Sandstone)

Heat in Place Method: Only Sandstone

1. Total mass (m_T):

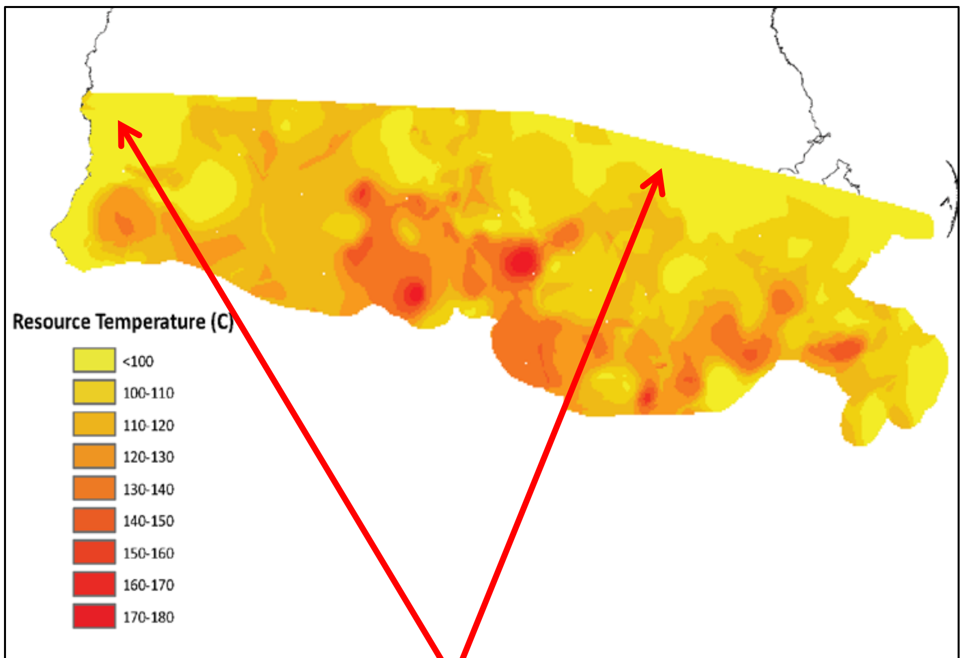
$$m_T = \varphi \cdot \rho \cdot A \cdot (z_{sand})$$

$$\rho = 0.25$$

2. Heat in place (J_T):

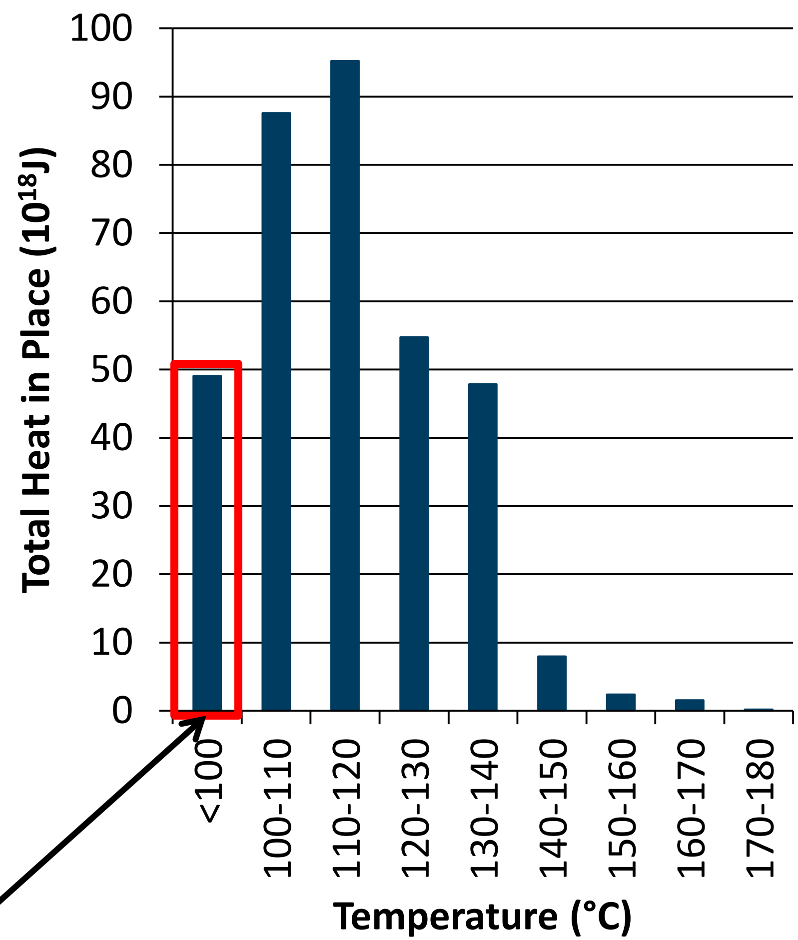
$$J_T = m_T \cdot c_P \cdot (T_R - T_0)$$

$$\text{with } T_0 = 25^\circ C$$



1) Multiple regions in Louisiana resource region have temperatures less than 100°C

Louisiana: Heat in Place (Sand)



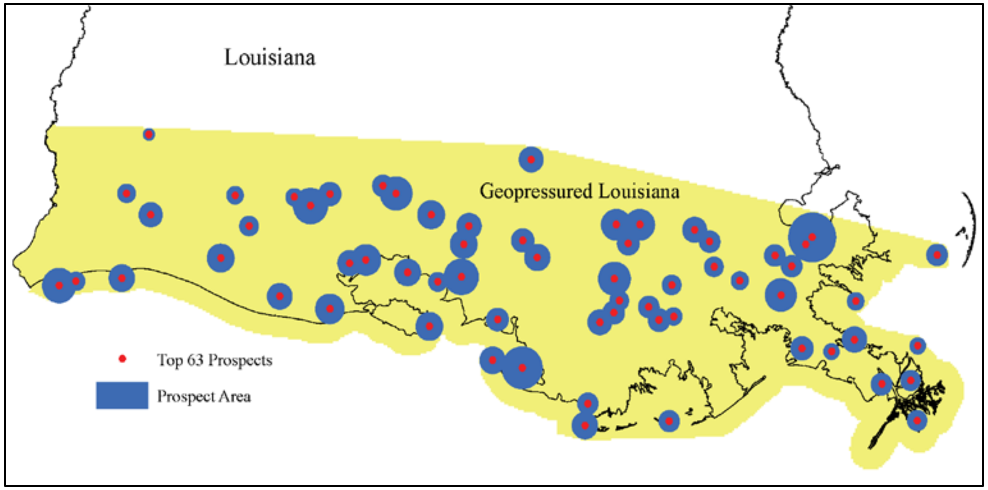
2) Large portion of resource below 100°C

Formation	Total (J)
Louisiana	3.47E+20

Louisiana Recoverable Energy Estimates

Evaluation by Bassiouni (1980):

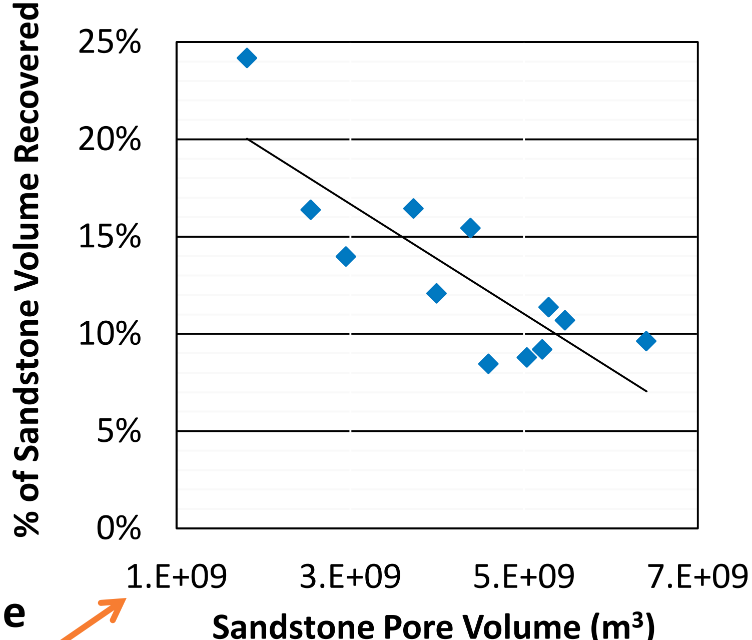
- For the top 63 prospects, recovered electrical energy was provided



- For the top 15 prospects sandstone pore volume was estimated using sandstone thickness

Recovery Factor Estimate:

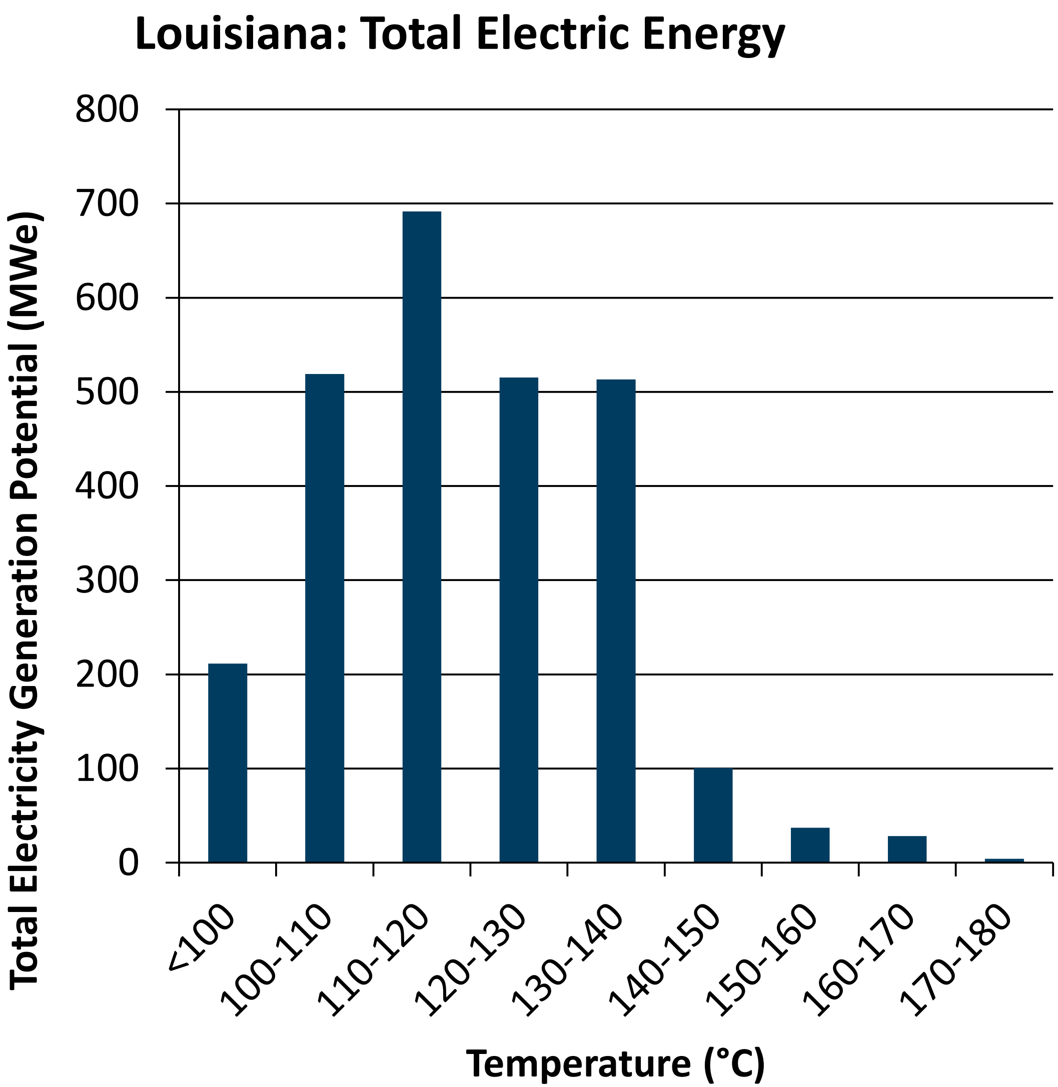
The total volume recovered for the top 15 prospects was estimated using assumptions presented in Bassiouni (1980). Recovery factors were estimated by dividing the estimated volume recovered by the sandstone pore volume.



$RF = -3E\text{-}11(VT \cdot \phi) + 0.2516$
$R^2 = 0.6915$

Louisiana recovery factor is much higher from the sandstone based on available data from Bassiouni (1980) than from Frio and Wilcox reservoir modeling

Louisiana Recoverable Energy

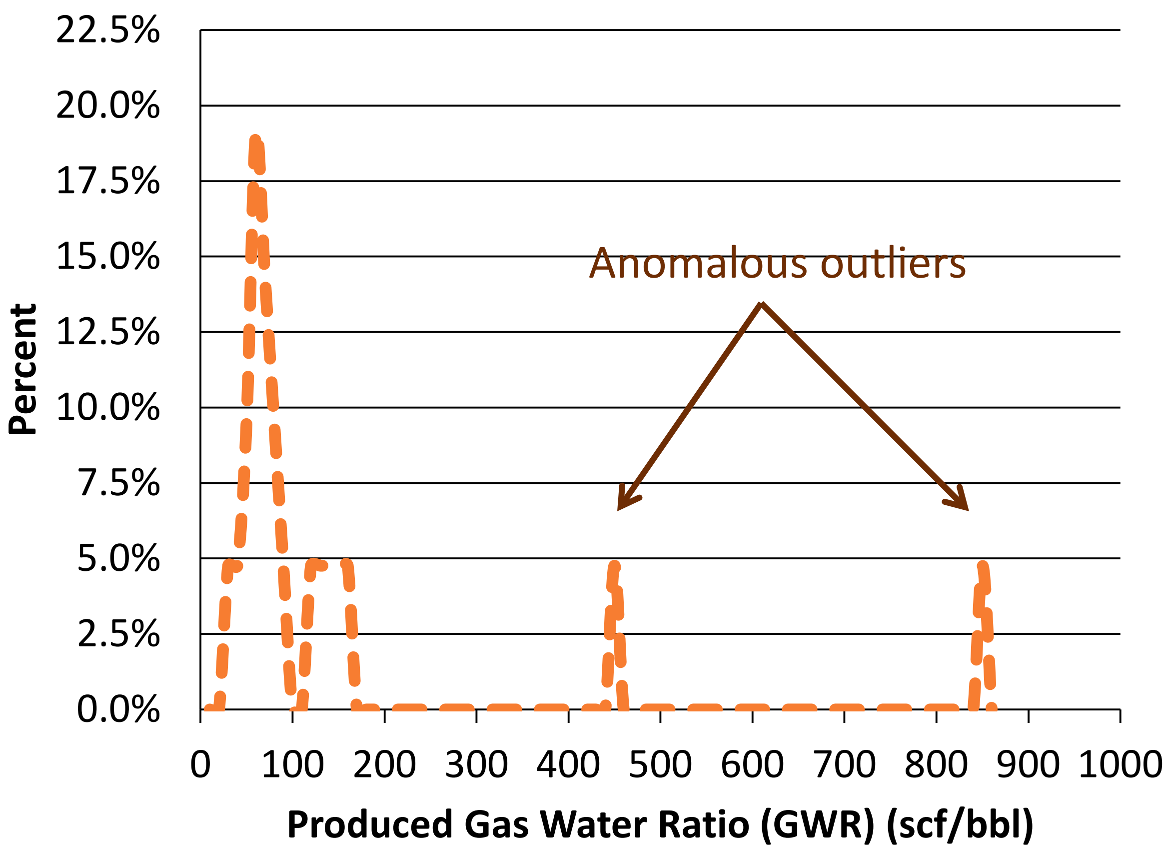


Formation	Total (MWe)
Louisiana	2620

Summary:
Due to high recovery factors for Louisiana based on results from Bassiouni (1980), the electric energy potential is equivalent to the five formations in Texas. This is true even though the resource is at on average a lower temperature and covers a smaller surface area.

Natural Gas Recoverability Estimate

Distribution of the Produced Gas Water Ratio from results of fairway reservoir modeling



Results from 19 of the 21 reservoir models excluding the two anomalous outliers were used to calculate GWR_{ave}

Summary:

- 10% < 45 scf/bbl
- 90% < 170 scf/bbl
- 53% between 45–85 scf/bbl

Natural Gas (V_{NG})

$V_{NG_A} = m_{wh} \cdot \rho^{-1} \cdot GWR_{ave}$

- ρ: density
- Density is a function of depth, pressure, and temperature (lb/bbl)
- GWR_{ave} : average produced gas water ratio from reservoir modeling results for all fairways at 83 scf/bbl

Source: Esposito and Augustine (2011)

Gulf Coast Total Recoverable Natural Gas

Formation	Total Natural Gas (scf)	Total Mass Produced (kg)	Average Flow Rate of Gas (MMscf/D)
Louisiana	9.52E+13	1.75E+14	13,040
Lower Wilcox	1.37E+13	2.49E+13	1873
Lower Frio	6.92E+12	1.25E+13	948
Vicksburg Jackson	6.82E+12	1.21E+13	934
Upper Claiborne	1.98E+12	3.66E+12	272
Lower Claiborne	9.52E+11	1.51E+12	114
Total	**1.25E+14**	**2.29E+14**	**1.71+04**

Assumptions:

1. All fluid is fully saturated with natural gas at reservoir conditions
2. Some free phase gas is present in the pore space representing between 1%–5% of pore volume
3. Presence of potential gas layers is not included in estimate

Results and Conclusions

- Estimated recoverable electricity generation potential:
  - Texas: 2.5 GW
  - Louisiana: 2.6 GW
- Highest quality resource is in southern Vicksburg Jackson due to collocation of high temperatures and thick sands
  - Total of ~1,000 MW electricity generation potential
- Large quantity of natural gas could be produced in conjunction with geopressured geothermal resource
  - 1.25×10^{14} scf of natural gas
- More data for each formation as well as data on sandstone permeability would improve overall analysis
- Louisiana estimate is quite high and is based on limited data on recovery factors. Should be treated as less certain than estimate for Texas.

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THANK YOU!

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