# Using Bayesian Belief Networks to Evaluate Continuous Gas Resources (Shale Gas, Tight Gas, and Coal Bed Methane): Tools to Calibrate the Expert and Exploit Knowledge*

**Kurt J. Steffen**[1]

Search and Discovery Article #40571 (2010)
Posted July 30, 2010

* Adapted from an oral presentation at AAPG Annual Convention and Exhibition, New Orleans, Louisiana, USA, April 11-14, 2010

[1]Exploration Company, ExxonMobil, Houston, TX. (kurt.j.steffen@exxonmobil.com)

## Abstract

In Unconventional Resources (Shale Gas, Tight Gas, and Coal Bed Methane), the hydrocarbon system elements (source, reservoir, seal, hydrocarbon recovery, etc.) are controlled by the properties of a single lithology or closely spaced groups of lithologies. The ability to commercially extract natural gas from Unconventional Resources represents the primary risk in these resource types, and the commerciality of a particular play varies spatially within the region of hydrocarbon occurrence. Therefore, it is critical to identify and evaluate the commerciality of Play Fairways (aka Sweet Spots) and differentiate these fairways from non-commercial areas.

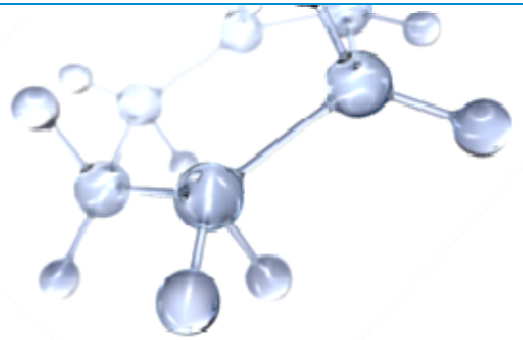
Although the properties of a single lithology can control Unconventional Resource commerciality, the properties of that single lithology represent the complex interaction of sedimentation and basin/tectonic evolution. In addition, Unconventional Resources require artificial stimulation (generally hydraulically induced fractures) in order to produce gas at commercial rates. Understanding/predicting commerciality in Unconventional Resources therefore requires understanding of a complex natural system and how that system will respond to engineering intervention.

In comparison to the complexity of the system, geoscientists generally have little data of sufficient quality to apply machine-learning techniques. Expert systems such as Bayesian Belief Networks (BBN) are being used successfully to evaluate Unconventional Resources. BBNs are used: 1) to break the complex system into smaller, tractable pieces; 2) as a flexible tool to incorporate beliefs based on theory, empiricism, and tacit expert knowledge; 3) to manage system and input uncertainty; and 4) to improve expert understanding, improve communication, and as a tool to teach new practitioners.

To exploit the power of BBNs as a predictive tool, numerous tools that link BBNs to Geographic Information System (GIS) data have been developed within ExxonMobil. These tools: 1) Allow for output maps to be created based on BBN output and GIS based inputs 2) Visualize probabilistic output. 3) Aggregate probabilistic results to summarize resource estimates for areas of interest. In addition, a GIS enabled database of calibration data has been created that allows for the comparison of BBN predictions to actual results. The expert uses these validation tools to improve predictive ability and gain insight into Unconventional Resources systems.

Copyright © AAPG. Serial rights given by author. For all other rights contact author directly.

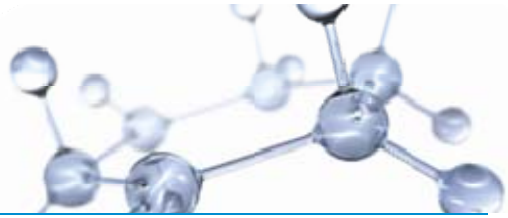
ExxonMobil Exploration



# Using Bayesian Belief Networks to Evaluate Continuous Gas Resources (Shale Gas, Tight Gas, and Coal Bed Methane): Tools to Calibrate the Expert and Exploit Knowledge.

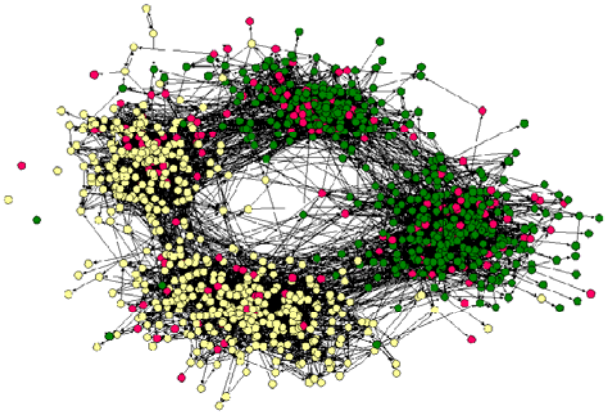
Kurt Steffen, PhD

# Bayesian Belief Networks (BBNs)



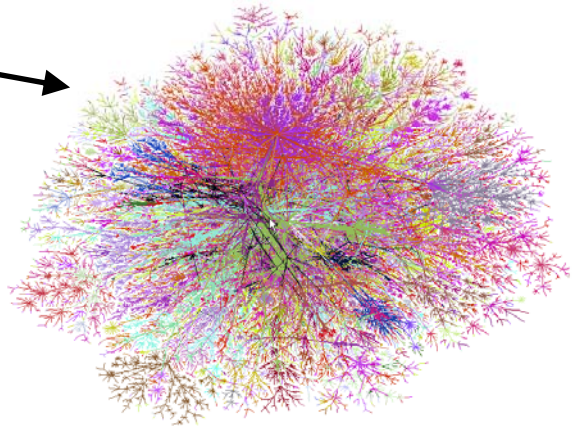
- Uses a Causal Net to quantify relationships.
- BBNs break understanding of the system into small, tractable piece
- BBNs are very flexible, we can use multiple sources to quantify the relationships as well as calibrate the results
- Acknowledges the multi-variable, complex nature of Unconventional Resources
- Because the process is automated, large numbers of polygons can be run thru the system, approximating the continuous nature of the continuous resource.
- Less sensitive to arbitrary “cut-offs” if well calibrated

## Network: A description of things and their connections



The Internet

(Web sites, Links)

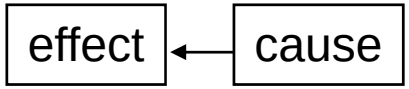


High School Dating

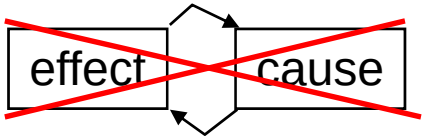
(People, Relationships)

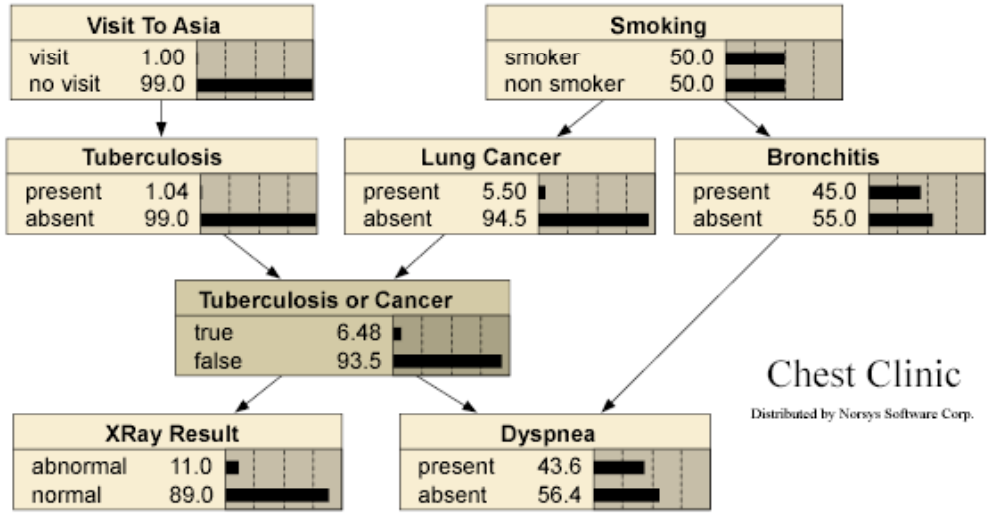
# Bayesian Belief Network (Variables, Causal Relationships)

BBNs are directed, causal:

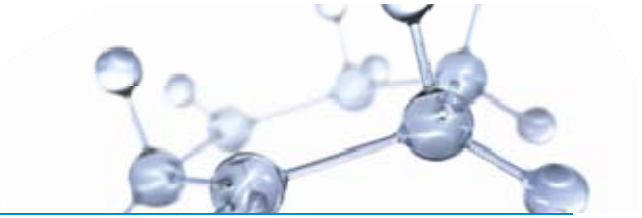



BBNs cannot contain cycles:



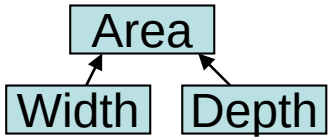



# Bayesian



A causal Belief Network for the area of a rectangle:

| Algebraic | Probabilistic |
|---|---|
| Area = Width*Depth | p(Area\|Width,Depth) |




Read as: The Probability of Area given Width and Depth

The algebraic case can easily be handled by multiplication and the probabilistic case could be handled with Monte Carlo Techniques

What if someone asks “If I give you the Area and the Width, can you tell me what the Depth is?”

| Algebraic | Probabilistic |
|---|---|
| Depth = Area/Width | p(Depth\|Area,Width) |

**Bayes’ theorem** allows us to calculate p(Depth|Area,Width) using the Belief Network shown above.

Therefore we can build a single causal network that also allows inference of the causes based on knowledge of the effects.

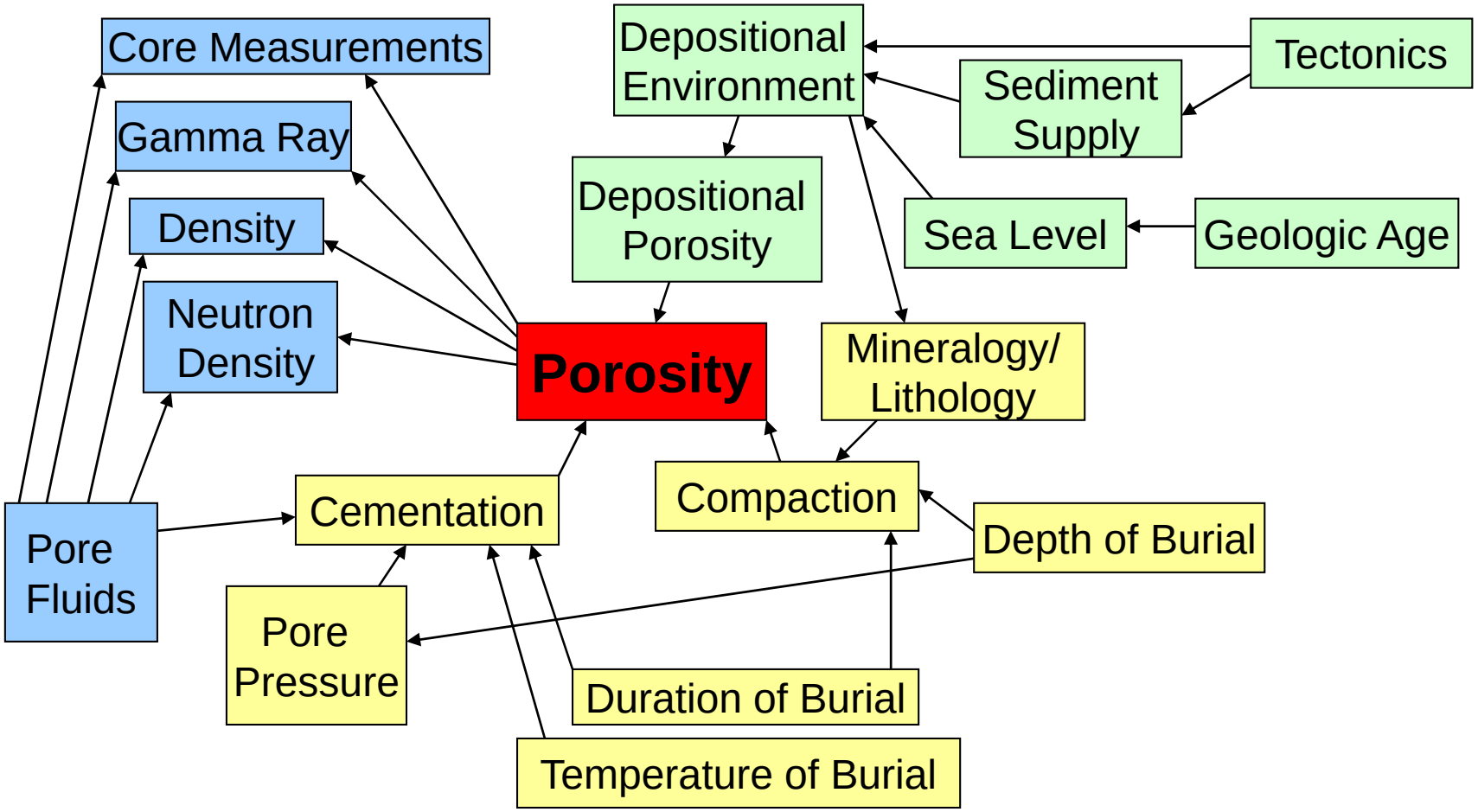
In short we can update our understanding based on adding knowledge about any variable in the network

**Thomas Bayes** (c. 1702 – 7 April 1761) was a British mathematician and Presbyterian minister, known for having formulated a specific case of the theorem that bears his name: **Bayes' theorem**, which was published posthumously.

ExxonMobil Exploration

# BBNs are an “Expert System”

## Captures Expert Knowledge/Beliefs



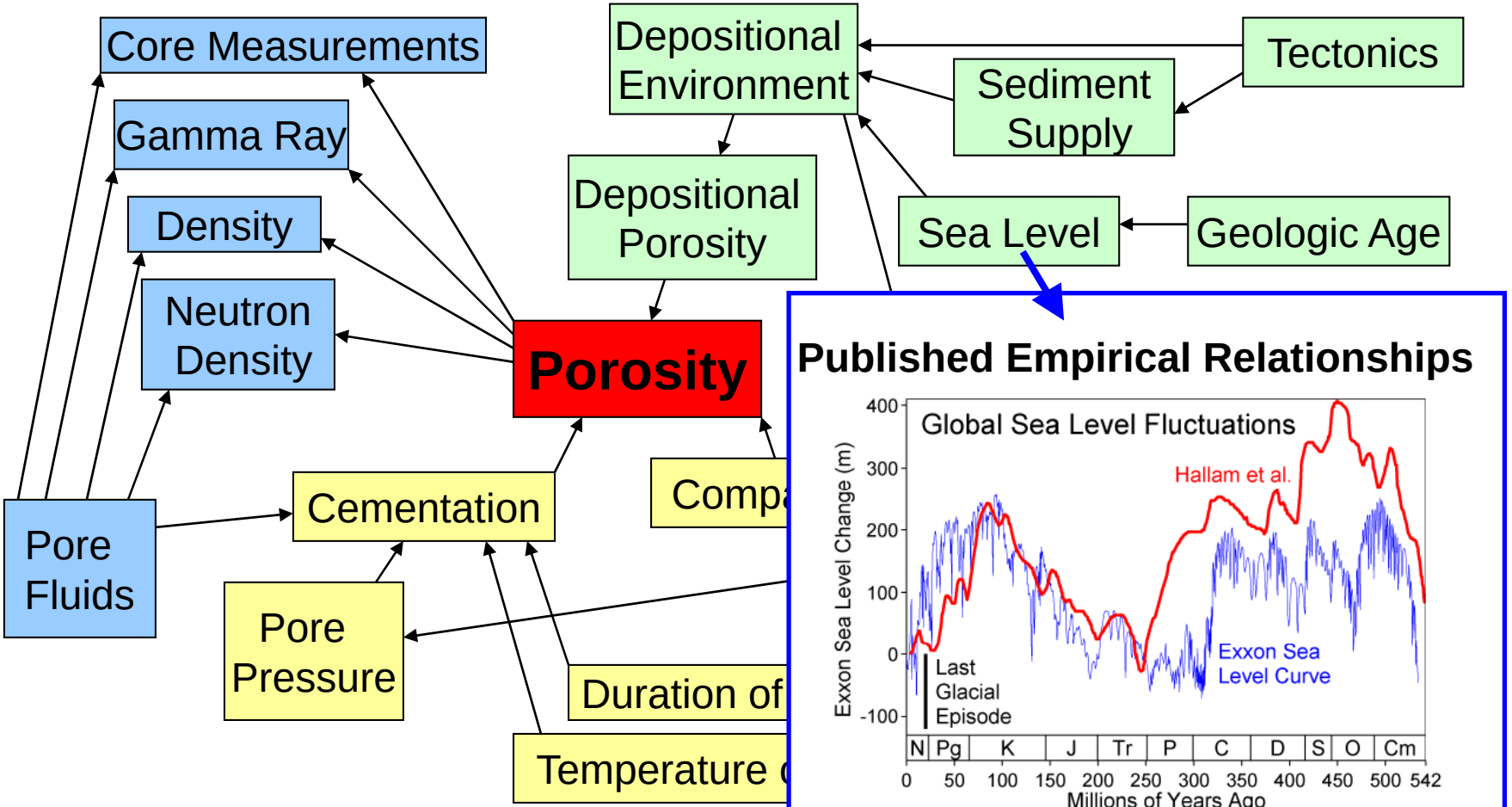

**Cause** → **Effect**



ExxonMobil Exploration

# BBNs are an “Expert System”

## Captures Expert Knowledge/Beliefs



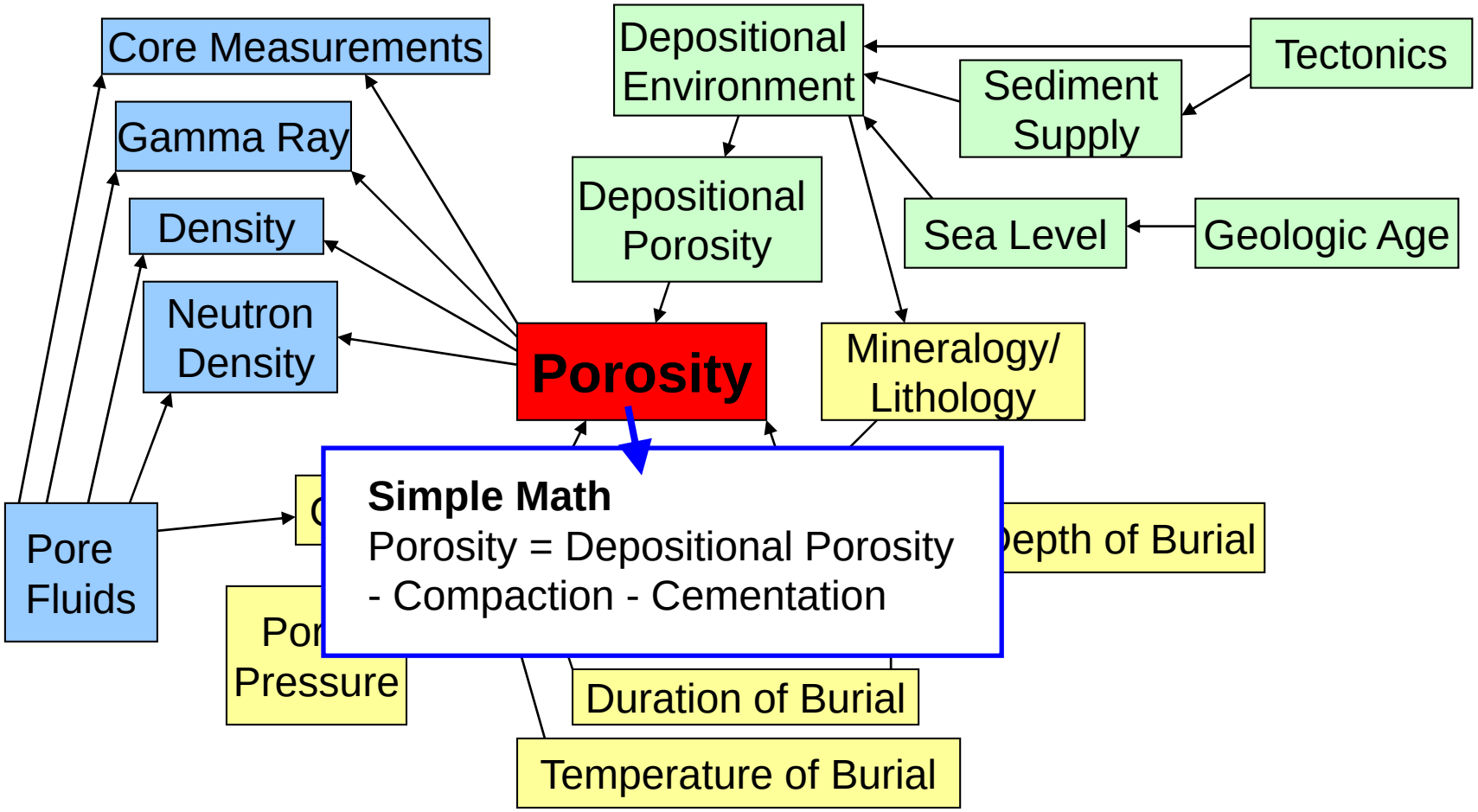

**Cause** → **Effect**



Exploration

# BBNs are an “Expert System”

## Captures Expert Knowledge/Beliefs



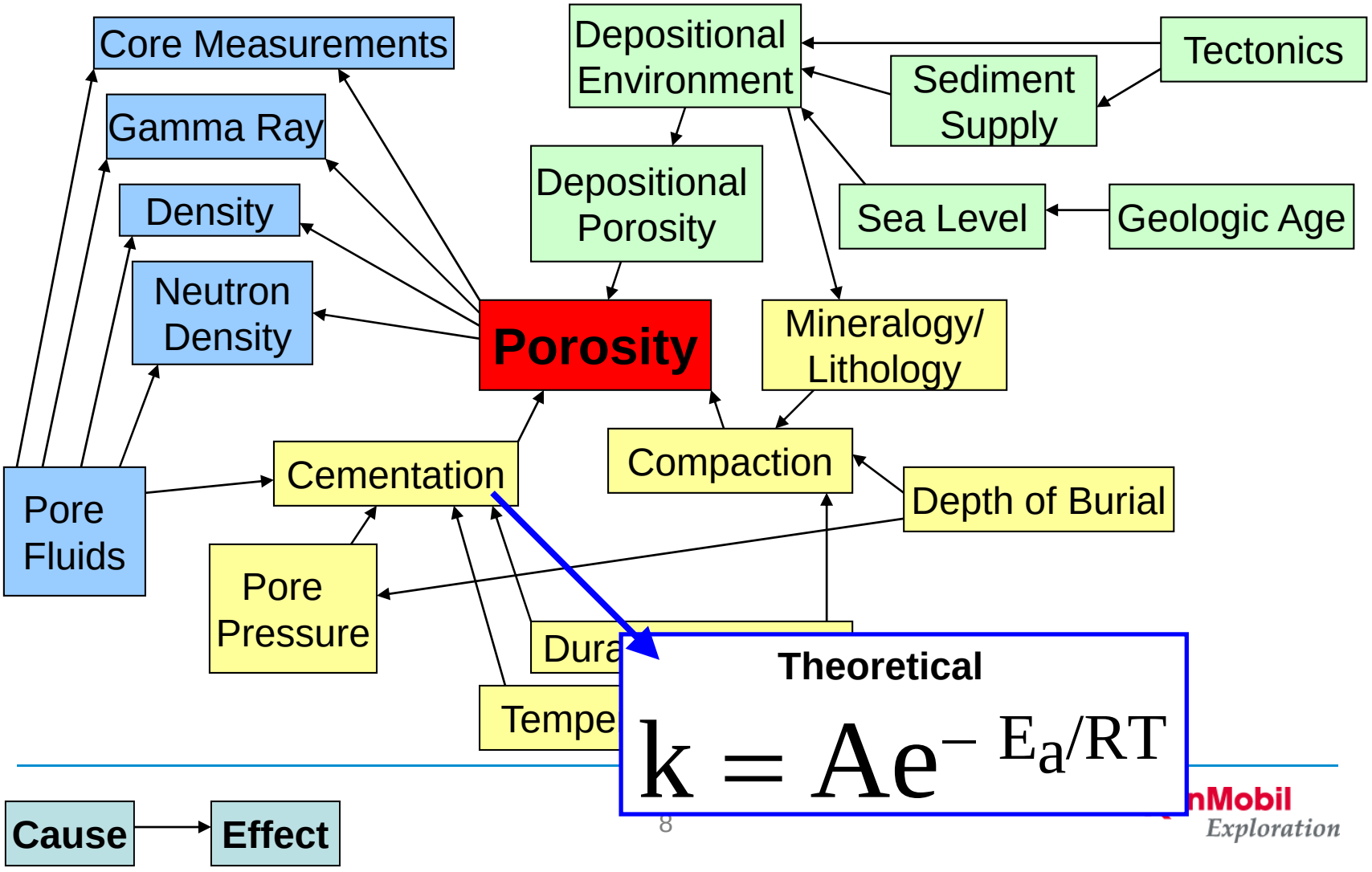

**Cause** → **Effect**



ExxonMobil Exploration

# BBNs are an “Expert System”

## Captures Expert Knowledge/Beliefs

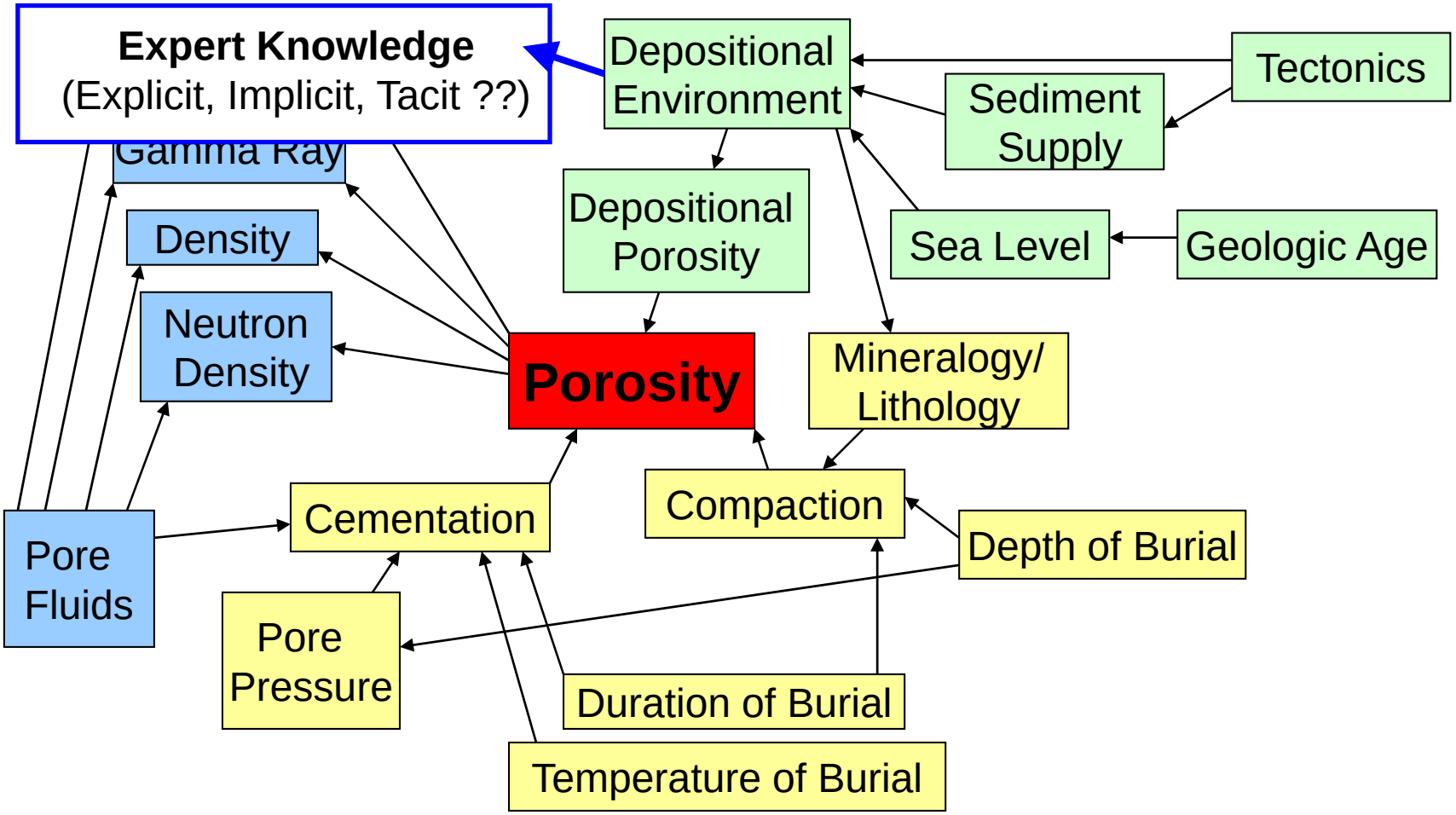





ExxonMobil Exploration

# BBNs are an “Expert System”

## Captures Expert Knowledge/Beliefs

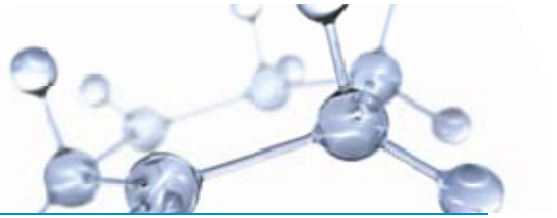



**Cause** → **Effect**



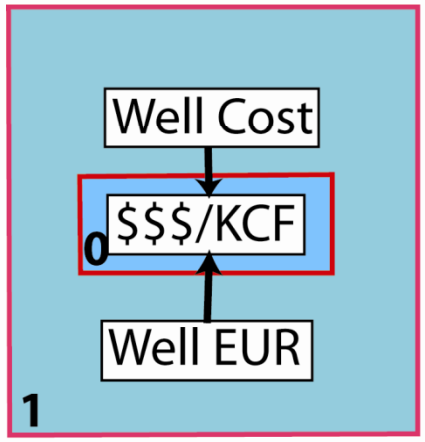
ExxonMobil Exploration

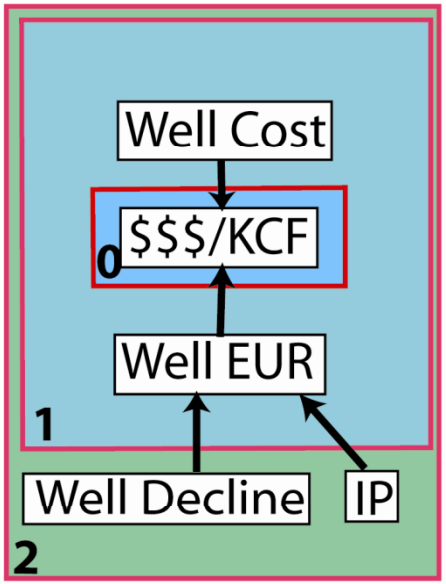
# Why BBNs for Unconventional Gas Resource Evaluation?

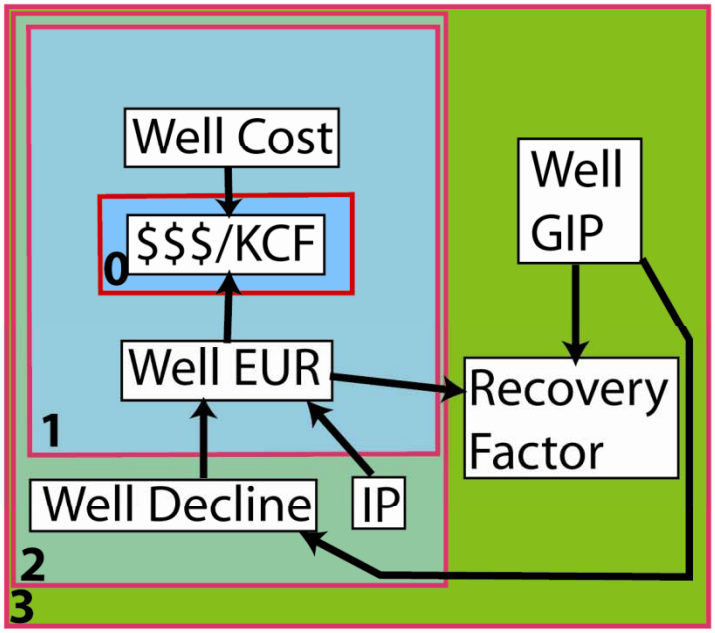


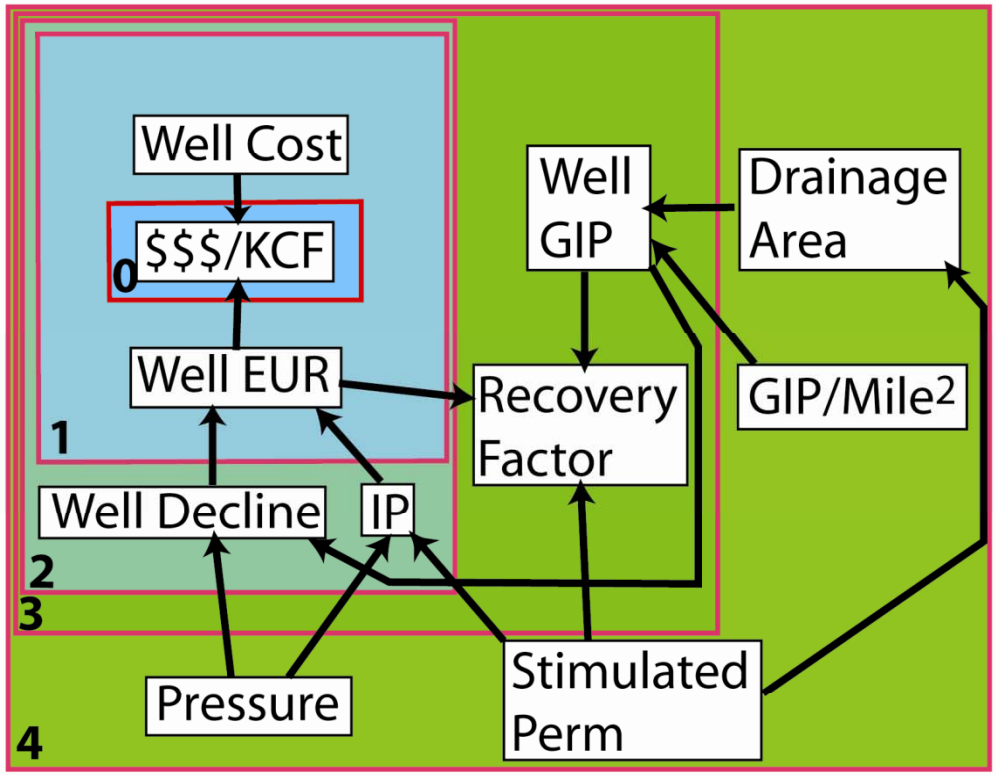
- In Unconventional Resources (Shale Gas, Tight Gas, and Coal Bed Methane) the hydrocarbon system elements are largely controlled by the properties of a single lithology or closely spaced groups of lithologies.
- The ability to commercially extract natural gas from Unconventional Resources represents the primary risk in these resource types, and the commerciality of a particular play varies spatially within the region of hydrocarbon occurrence.
- It is critical to identify and evaluate the commerciality of Play Fairways (aka Sweet Spots) and differentiate these fairways from non-commercial areas.
- Although the properties of a single lithology can control Unconventional Resource commerciality, the properties of that single lithology represent the complex interaction of sedimentation and basin/tectonic evolution.
- Unconventional Resources require artificial stimulation (generally hydraulically induced fractures) in order to produce gas at commercial rates.
- Understanding/predicting commerciality in Unconventional Resources therefore requires understanding of a complex natural system and how that system will respond to engineering intervention.

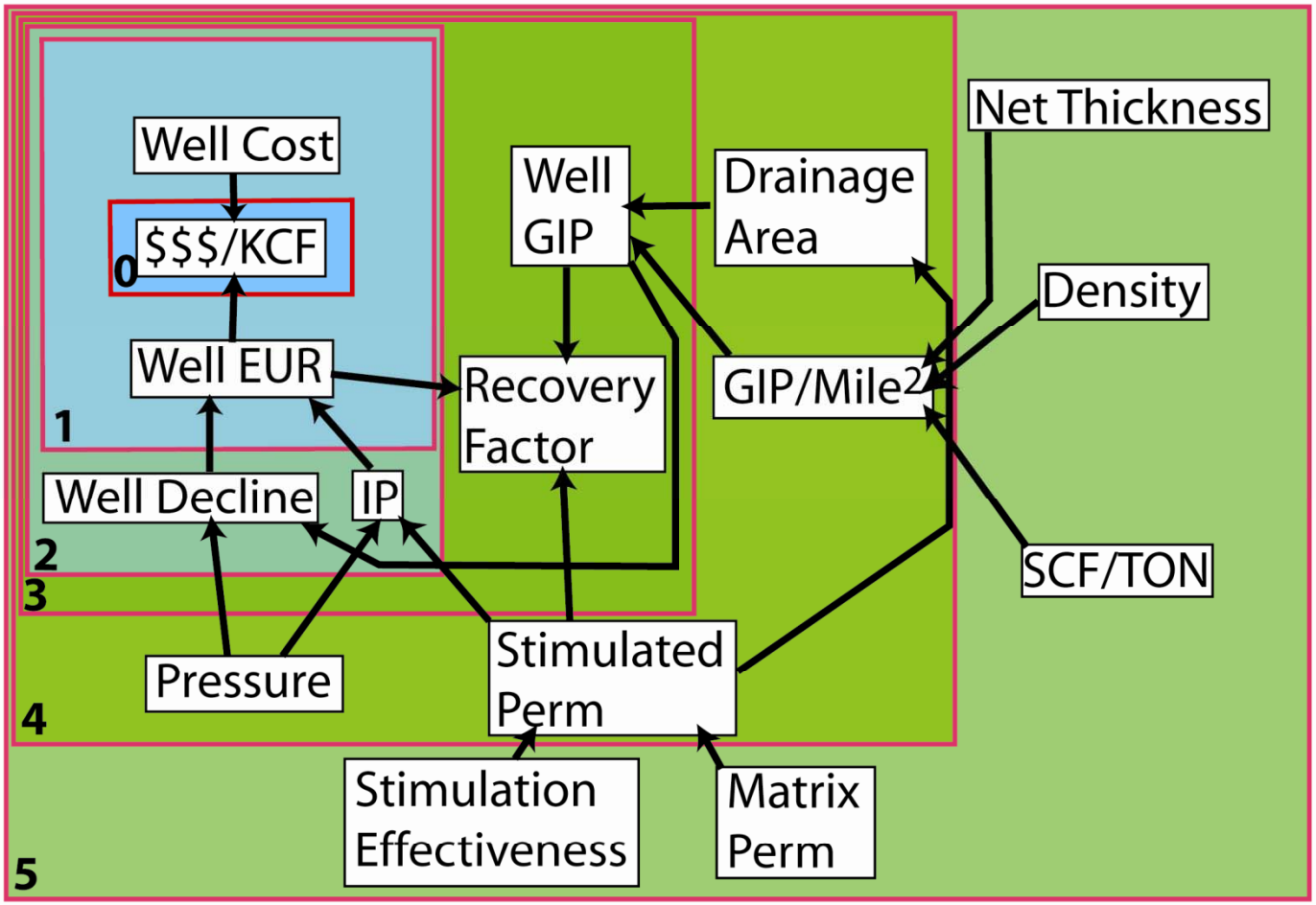
0
$$$/KCF

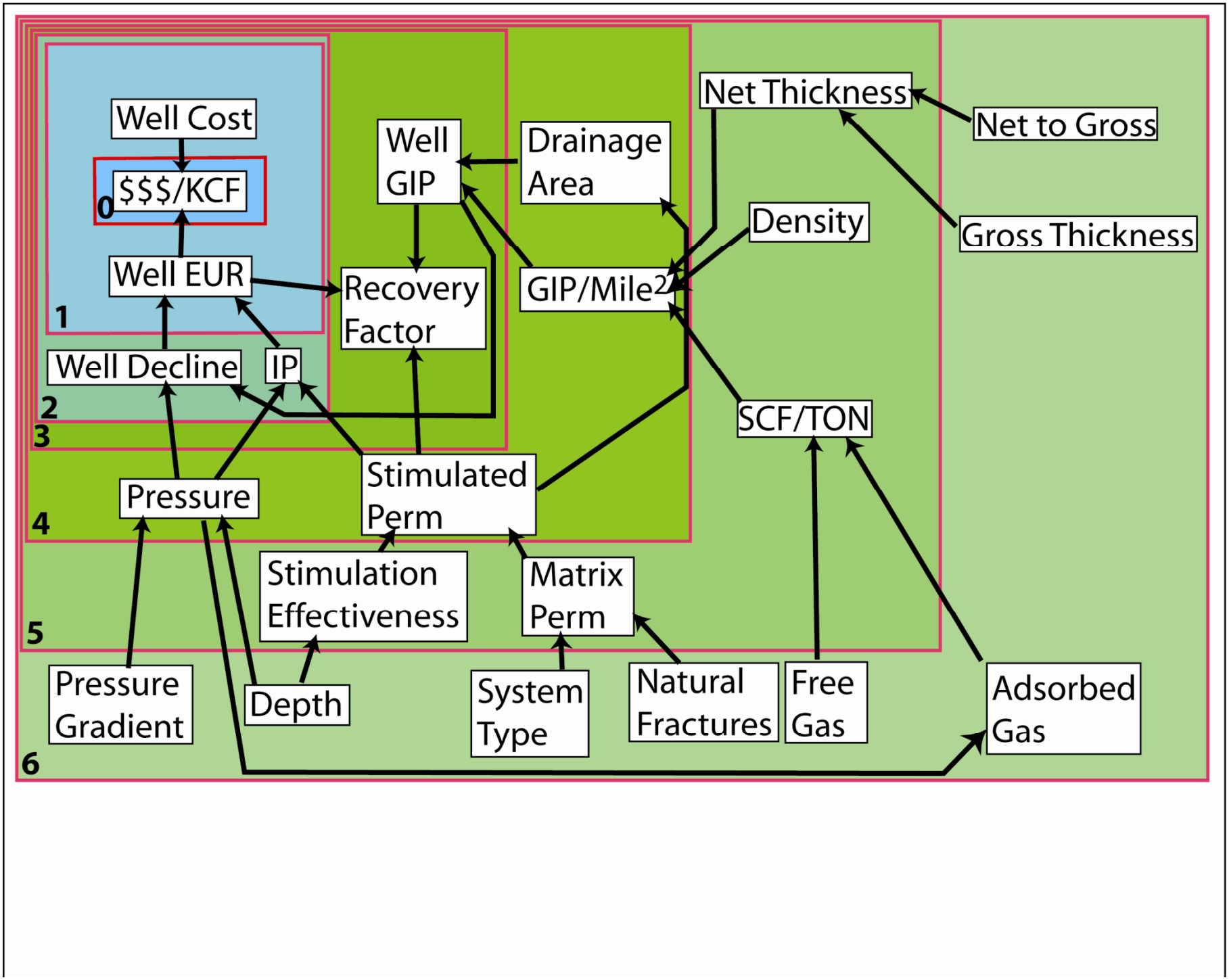

Well Cost
$$$/KCF
0
Well EUR
1

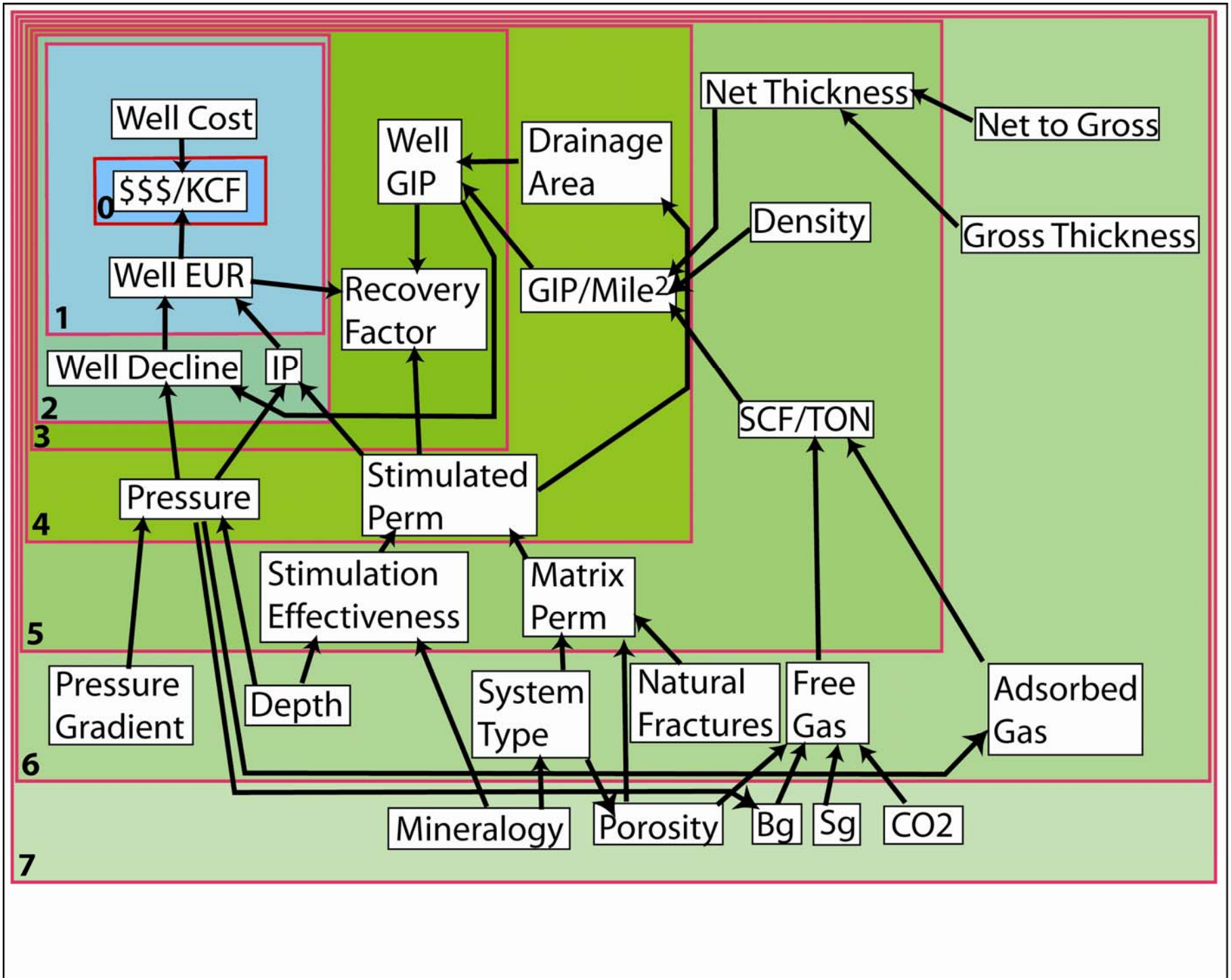

Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2

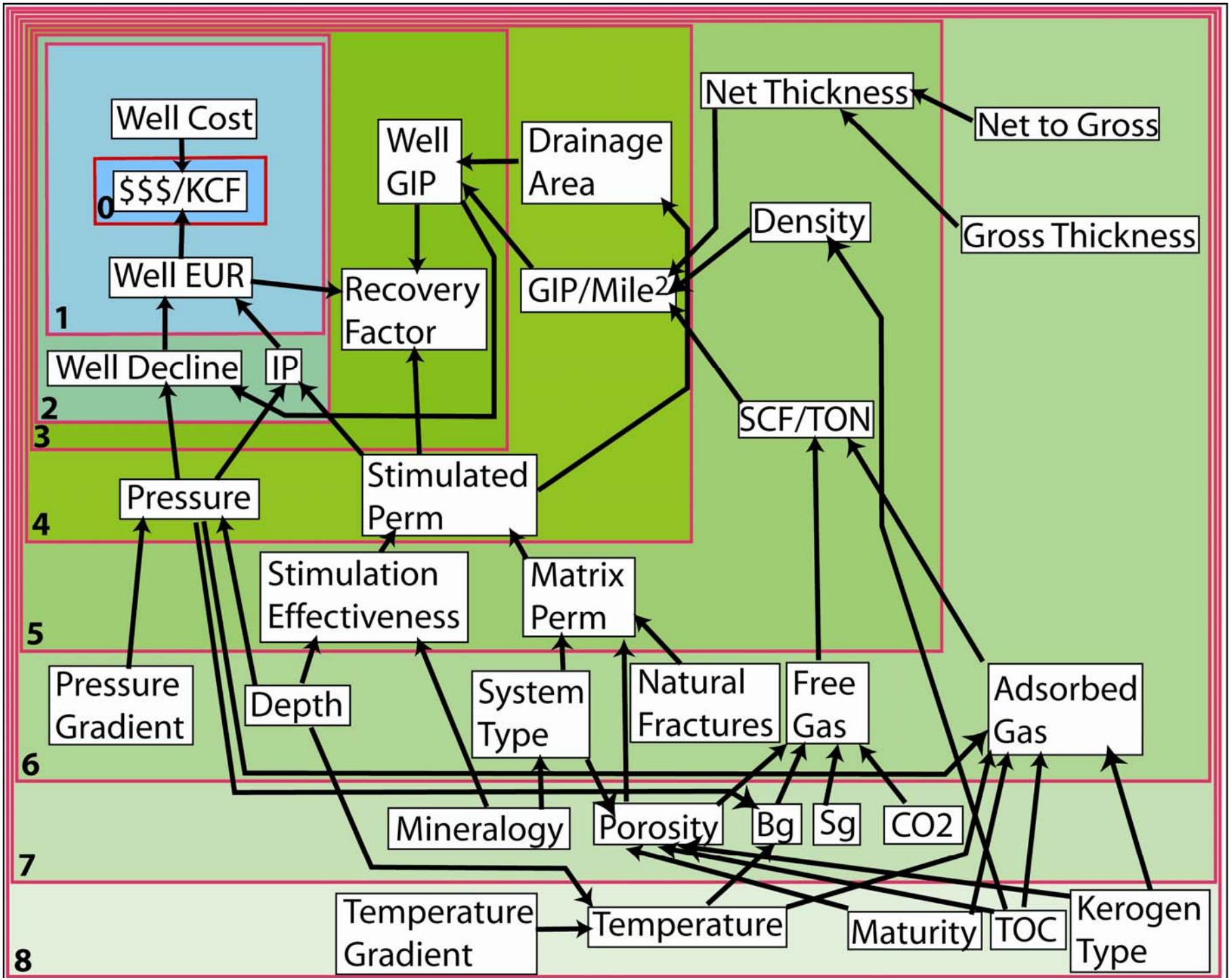

Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2
3
Well
GIP
Recovery
Factor

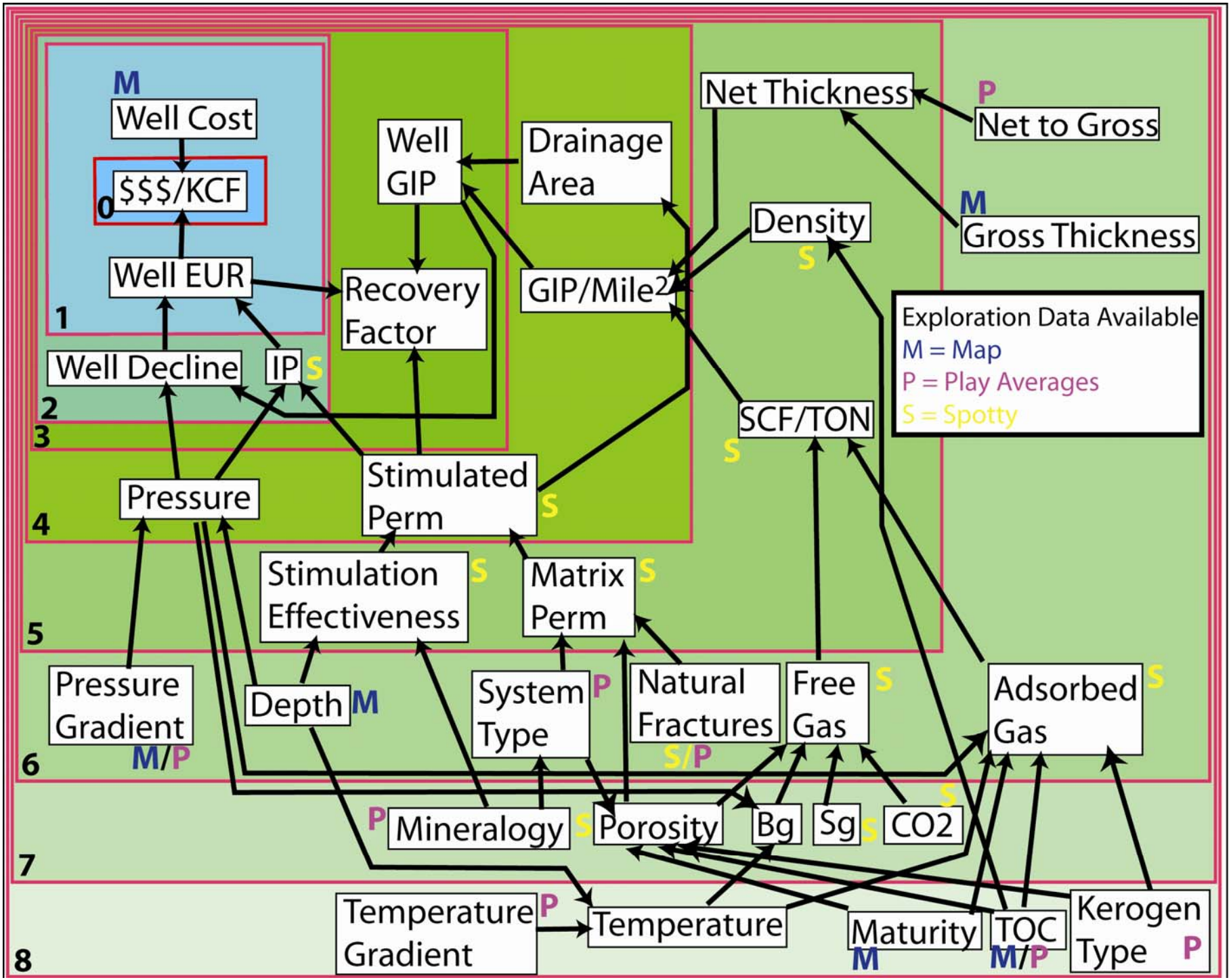

Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2
3
Pressure
4
Stimulated Perm
Recovery Factor
Well GIP
Drainage Area
GIP/Mile2

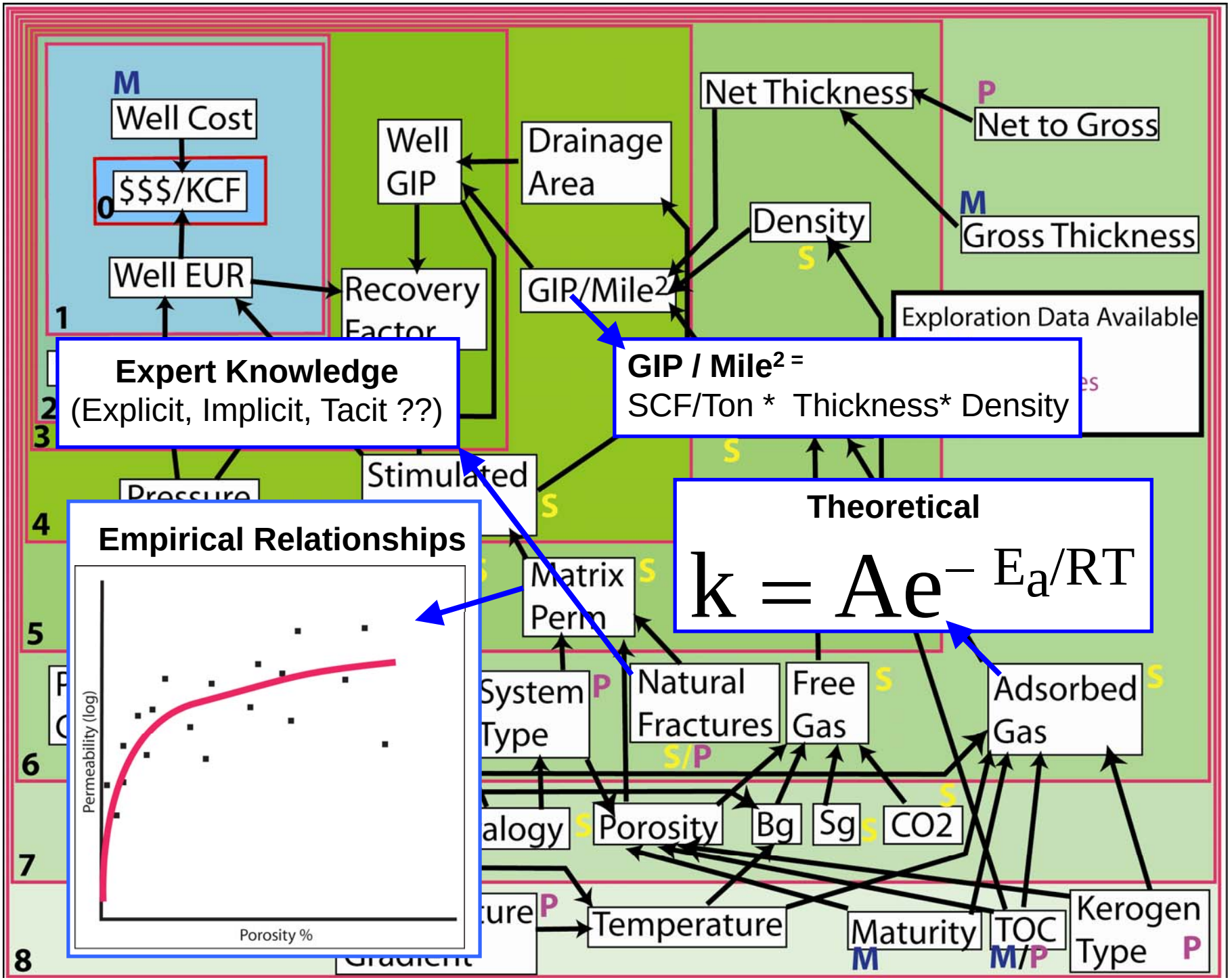

Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2
3
Pressure
4
Stimulation Effectiveness
5
Well GIP
Drainage Area
Net Thickness
Density
Recovery Factor
GIP/Mile2
SCF/TON
Stimulated Perm
Matrix Perm


Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2
3
Pressure
4
Stimulated Perm
Well GIP
Drainage Area
Recovery Factor
GIP/Mile2
Net Thickness
Net to Gross
Gross Thickness
Density
SCF/TON
Stimulation Effectiveness
Matrix Perm
5
Pressure Gradient
Depth
System Type
Natural Fractures
Free Gas
Adsorbed Gas
6

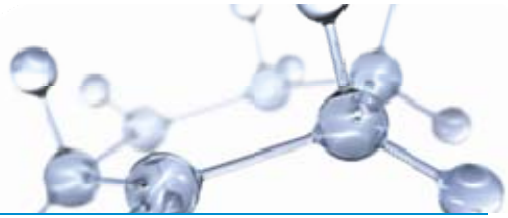

Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2
3
Pressure
4
Stimulated Perm
Well GIP
Drainage Area
Recovery Factor
GIP/Mile2
Net Thickness
Net to Gross
Gross Thickness
Density
SCF/TON
Stimulation Effectiveness
Matrix Perm
5
Pressure Gradient
Depth
System Type
Natural Fractures
Free Gas
Adsorbed Gas
6
Mineralogy
Porosity
Bg
Sg
CO2
7


Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
2
3
Well GIP
Drainage Area
Recovery Factor
GIP/Mile2
Net Thickness
Net to Gross
Gross Thickness
Density
SCF/TON
Stimulated Perm
Pressure
4
Stimulation Effectiveness
Matrix Perm
5
Pressure Gradient
Depth
System Type
Natural Fractures
Free Gas
Adsorbed Gas
6
Mineralogy
Porosity
Bg
Sg
CO2
7
Temperature Gradient
Temperature
Maturity
TOC
Kerogen Type
8


M
Well Cost
$$$/KCF
0
Well EUR
1
Well Decline
IP
S
2
3
Well GIP
Drainage Area
Recovery Factor
GIP/Mile2
Net Thickness
P
Net to Gross
M
Gross Thickness
Density
S
Exploration Data Available
M = Map
P = Play Averages
S = Spotty
SCF/TON
S
Stimulated Perm
S
Pressure
4
Stimulation Effectiveness
S
Matrix Perm
S
5
Pressure Gradient
M/P
Depth
M
System Type
P
Natural Fractures
S/P
Free Gas
S
Adsorbed Gas
S
6
P
Mineralogy
S
Porosity
Bg
Sg
S
CO2
S
7
Temperature Gradient
P
Temperature
Maturity
M
TOC
M/P
Kerogen Type
P
8

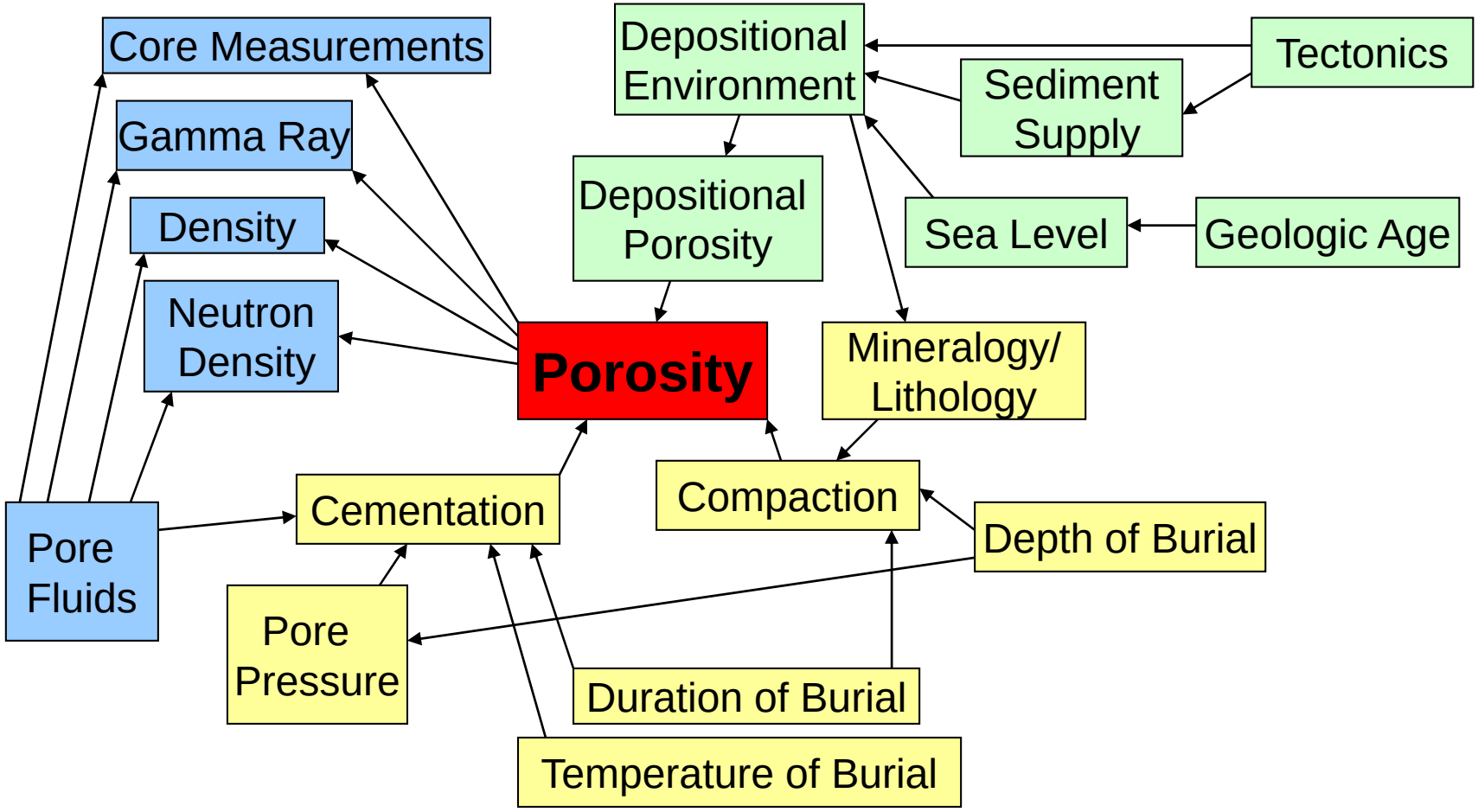

M
Well Cost
$$$/KCF
0
Well EUR
1
Well GIP
Drainage Area
Recovery Factor
GIP/Mile2
Net Thickness
P
Net to Gross
M
Gross Thickness
Density
S
Exploration Data Available
2
3
Expert Knowledge
(Explicit, Implicit, Tacit ??)
GIP / Mile2 =
SCF/Ton * Thickness* Density
Stimulated
S
4
Empirical Relationships
Permeability (log)
Porosity %
Theoretical
k = Ae− Ea/RT
Matrix Perm
S
5
System Type
P
Natural Fractures
S/P
Free Gas
S
Adsorbed Gas
S
6
alogy
S
Porosity
Bg
Sg
S
CO2
S
7
ure
P
Temperature
Maturity
M
TOC
M/P
Kerogen Type
P
8

# Exploiting the BBN: Linking to Maps



- To exploit the power of BBNs as a predictive tool, numerous tools that link BBNs to Geographic Information System (GIS) data have been developed within ExxonMobil.
- These tools:
  - Allow for output maps to be created based on BBN output and GIS based inputs
  - Visualize probabilistic output.
  - Aggregate probabilistic results to summarize resource estimates for areas of interest.
- A GIS enabled database of calibration data has been created that allows for the comparison of BBN predictions to actual results. These validation tools are used by the expert to improve predictive ability and gain insight into Unconventional Resources systems.

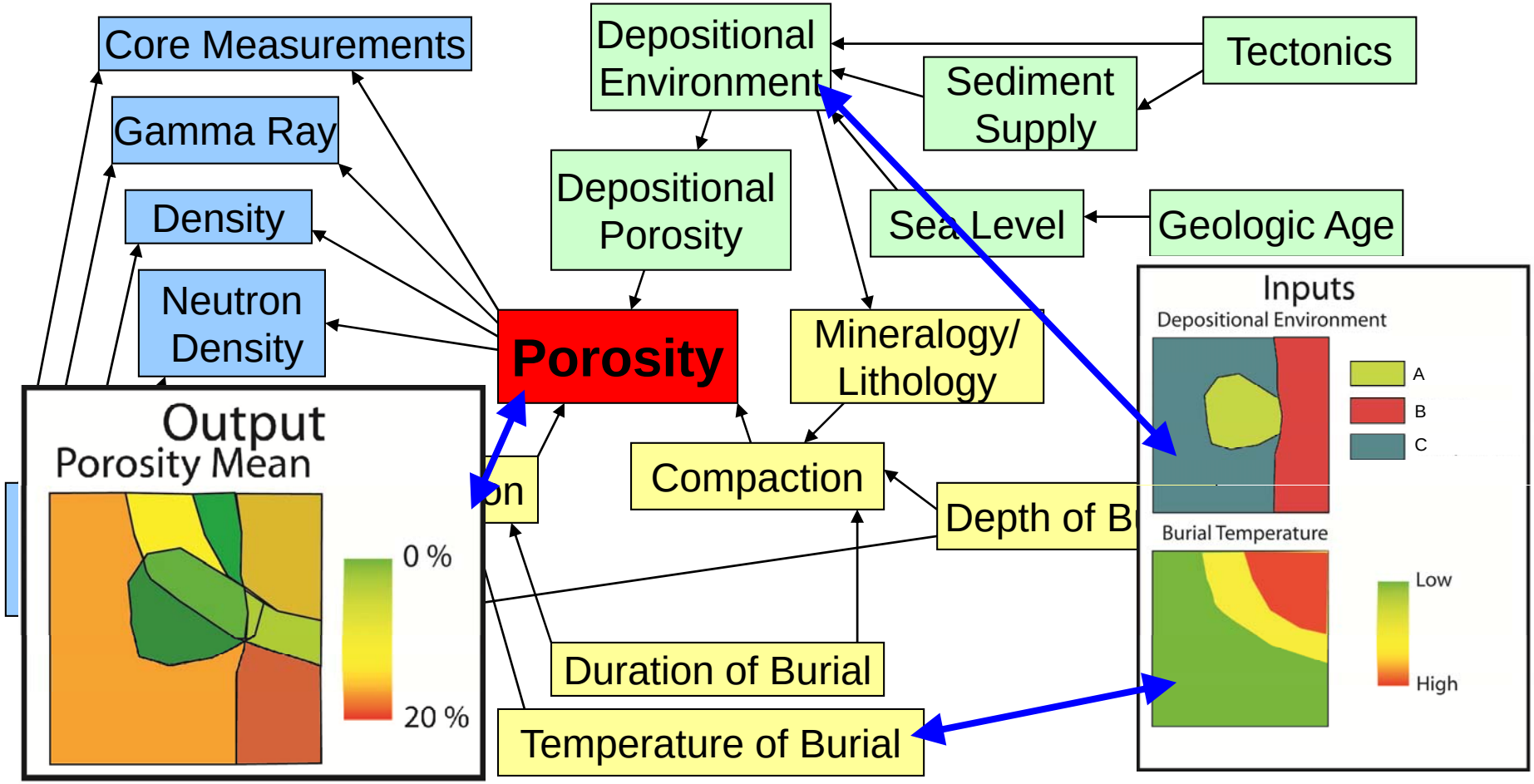
# Leveraging the Belief Network: Linking to Spatial Data






ExxonMobil Exploration

# Leveraging the Belief Network: Linking to Spatial Data

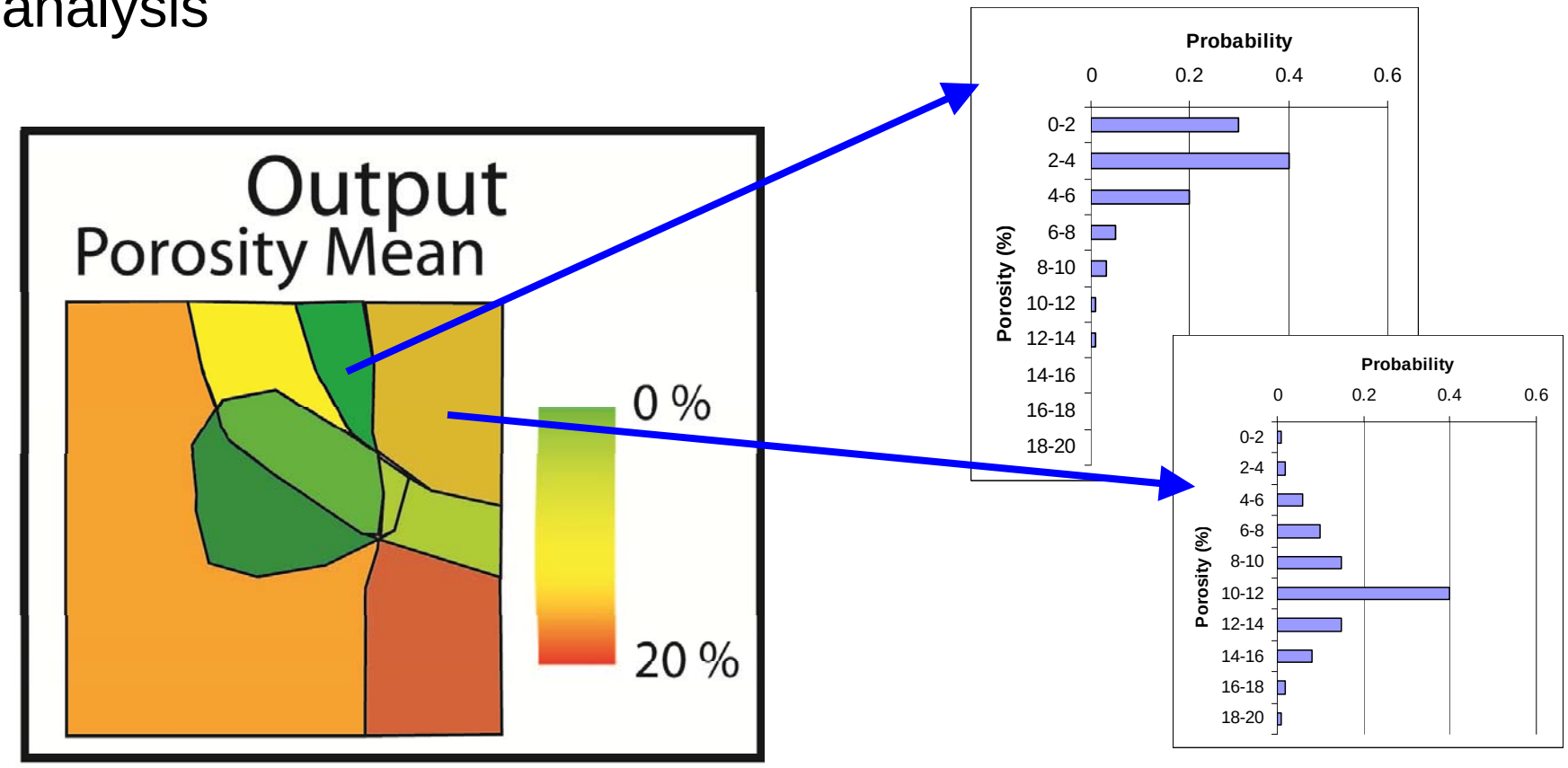





ExxonMobil Exploration

# Belief Networks Capture Uncertainty

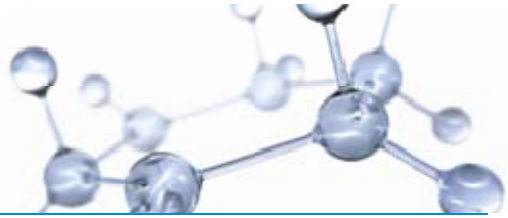
Although maps typically show the mean, median or most likely value the full statistical distribution is available for analysis






ExxonMobil Exploration

# Spatial Linkages can aid in Calibration/Validation of Belief Networks



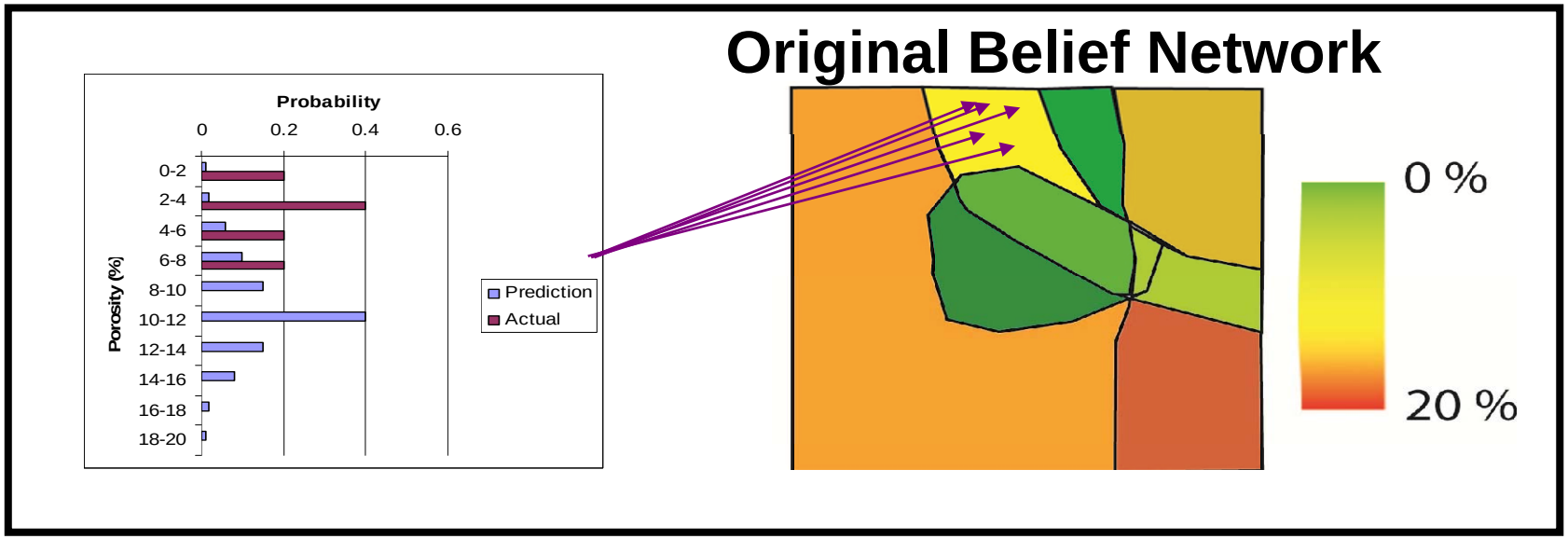
**Validation is a critical part of the process:**

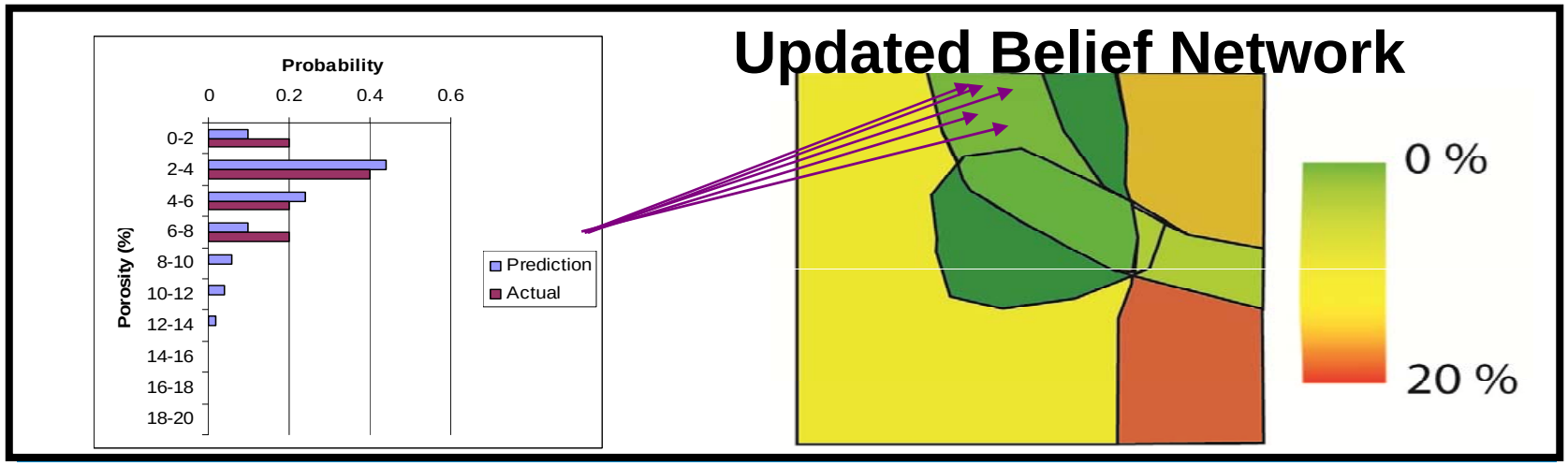
- **Validation can determine if the model is predictive (useful) or simply geo-fantasy**
- **The modifications to the expert's beliefs can "Make the Expert Smarter"**
- **The modifications to the Belief Network can be captured and exploited for future use (continual improvement and knowledge transfer)**
- **Expert judgment is required to determine if the validation data require change to the Network (Does this data change my beliefs?)**
- **Although available data sets may not be sufficient for machine learning purposes, they can often be used for validation with the expert "In the Loop"**



ExxonMobil Exploration

# Modifying Beliefs and the Network

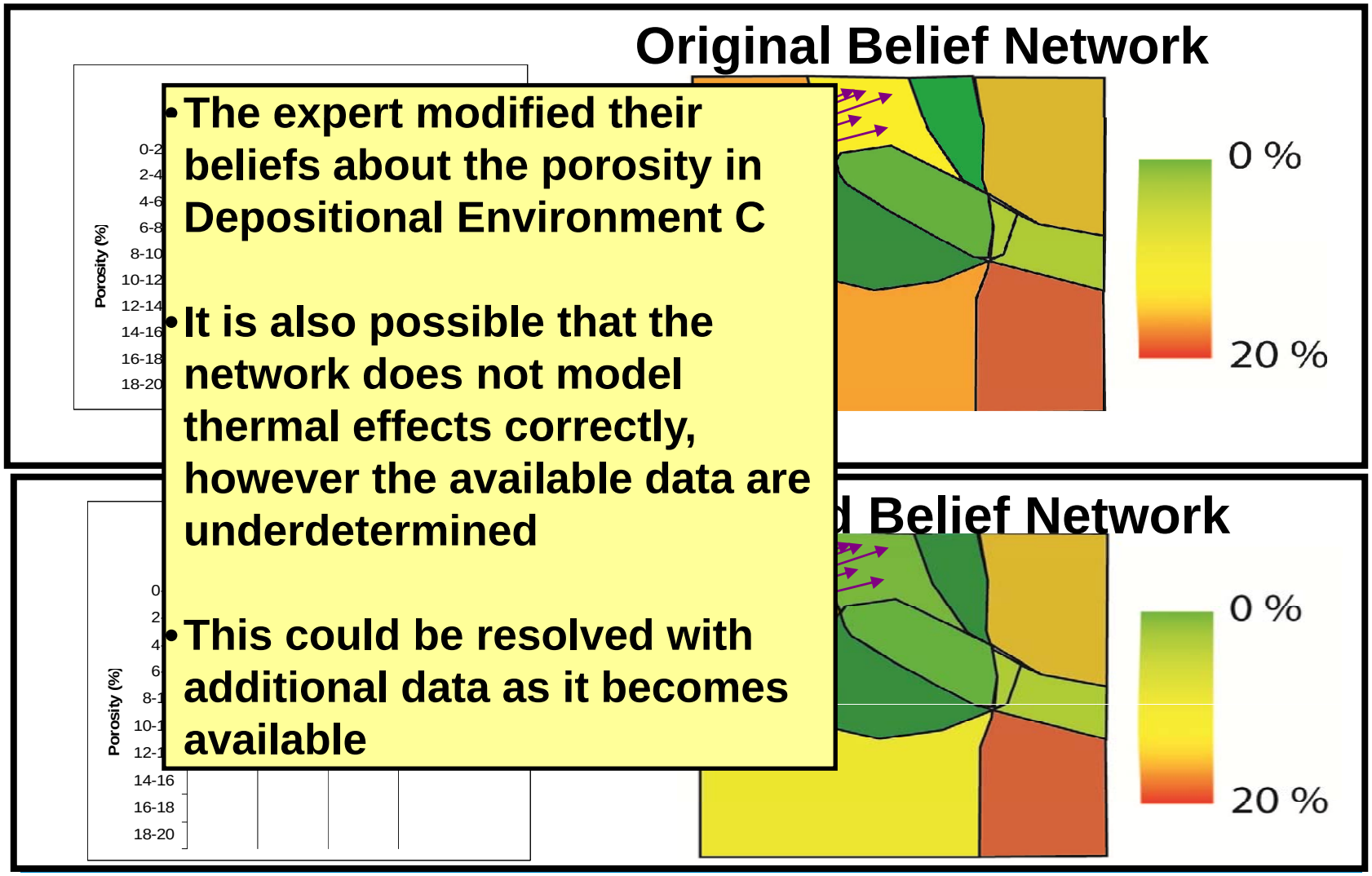





ExxonMobil Exploration

# Modifying Beliefs and the Network

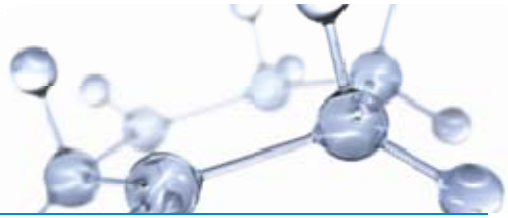


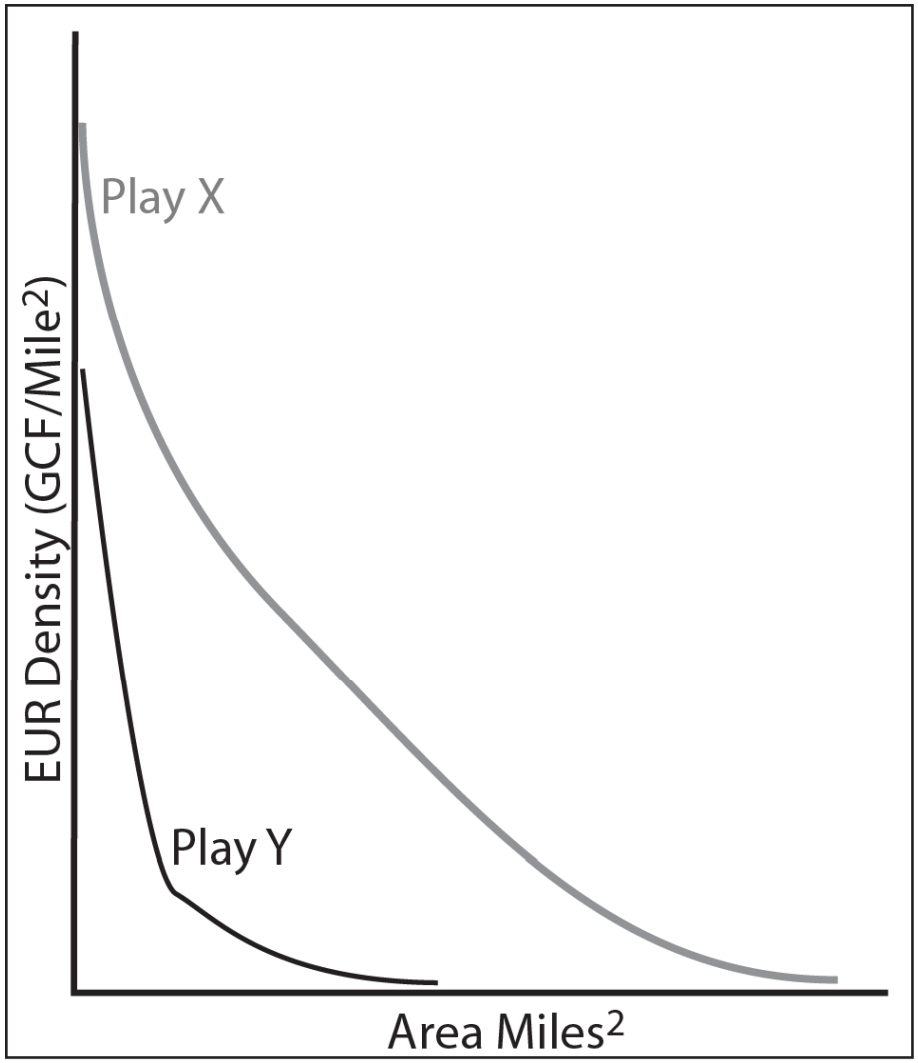

- The expert modified their beliefs about the porosity in Depositional Environment C
- It is also possible that the network does not model thermal effects correctly, however the available data are underdetermined
- This could be resolved with additional data as it becomes available



ExxonMobil Exploration

# Aggregation: Comparing Plays

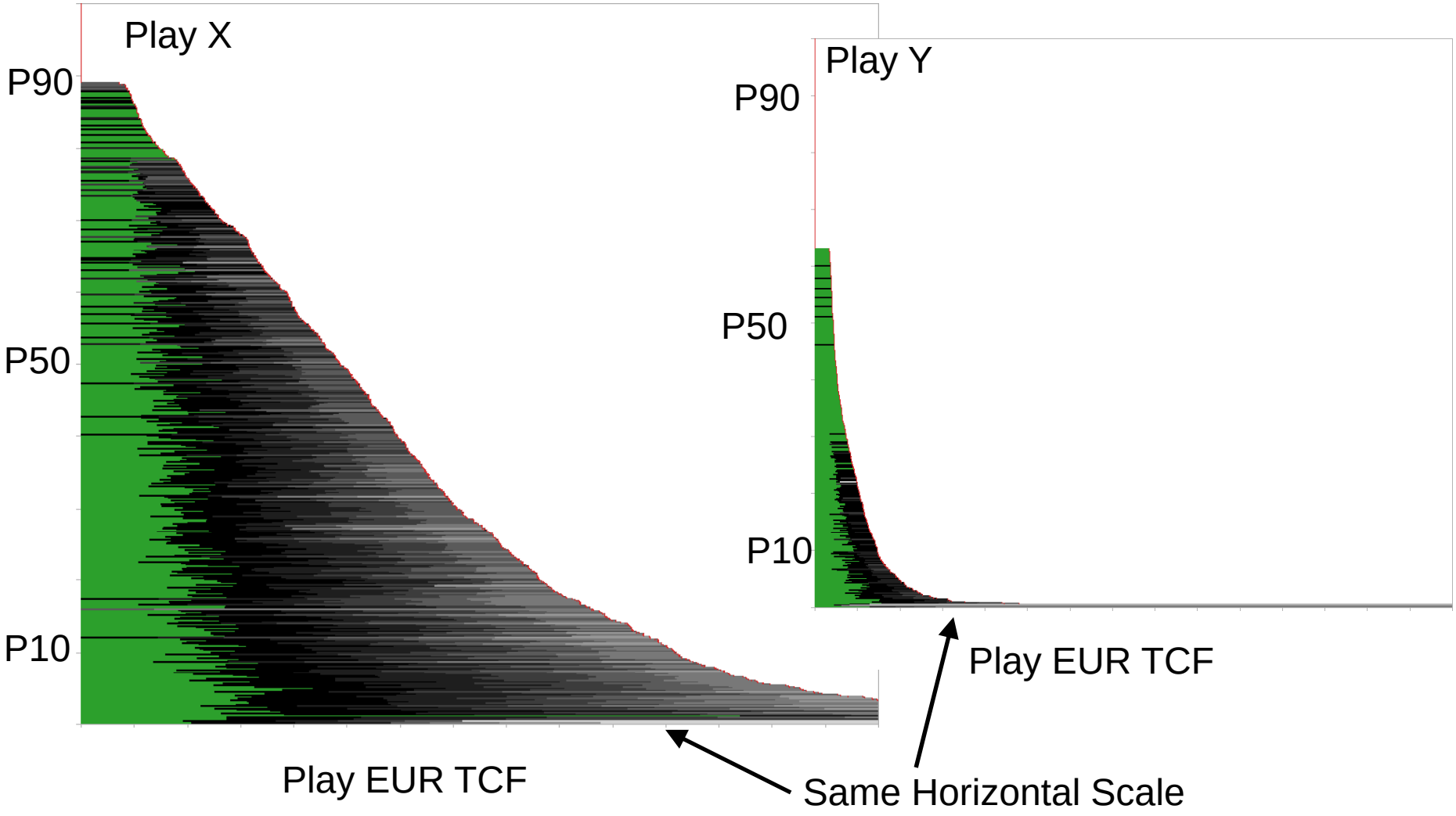







ExxonMobil Exploration

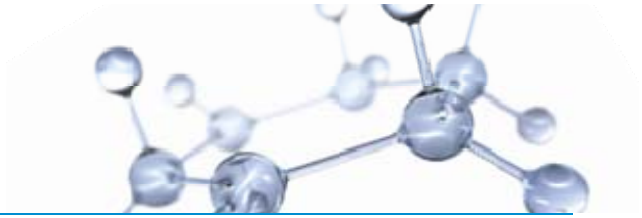
# Comparing Plays






ExxonMobil Exploration

# Conclusions



- BBNs provide an excellent tool to probabilistically model unconventional gas resources
- By breaking down the complex system in tractable pieces, different types of knowledge can be used to model different parts of the system.
- Validating the BBN is critical
- Linking BBNs to GIS systems provides an excellent opportunity to leverage the expert knowledge contained in the BBN and provides a rapid technique to evaluate continuous gas resources and the predictive capability of the BBN