Reducing Subjectivity in Geothermal Exploration Decision Making

2015 Stanford Geothermal Workshop
Palo Alto, California

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January 26, 2015

NREL/PR-6A20-63762
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

OVERVIEW

Background

- Geothermal Exploration Overview
- Typical Exploration Process
- Subjectivity in Exploration Decision Making

Methods

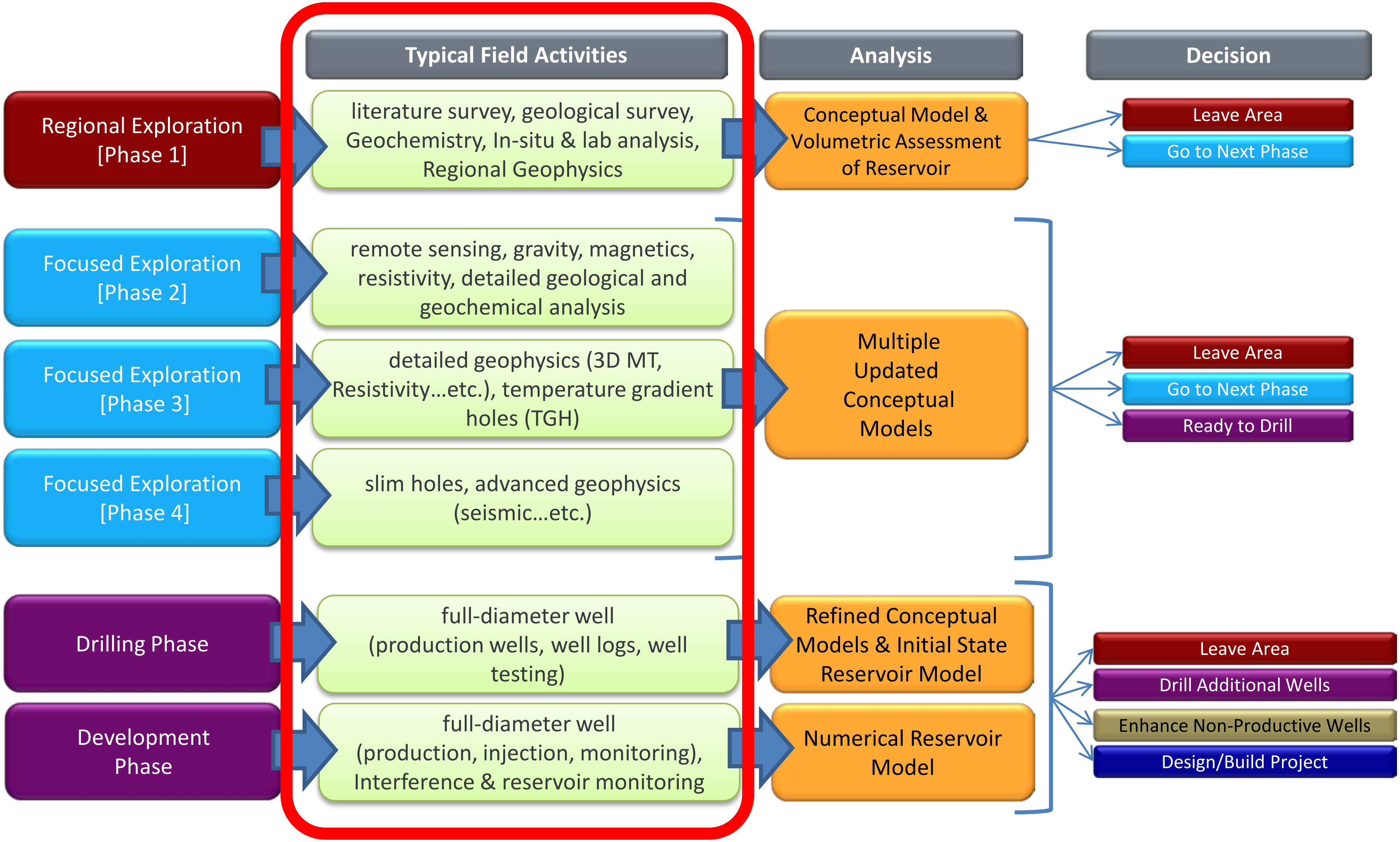
- Value of Information Analysis (VOIA)
  - Previous Applications of VOIA
  - Potential Expansion of use of VOIA
  - Additional work to be done
- Exploration Targeting (ETA)
  - Potential Application of ETA
  - Additional work to be done

Discussions

Dixie Valley, Northern Nevada

BACKGROUND

Typical Exploration Process - Schematic



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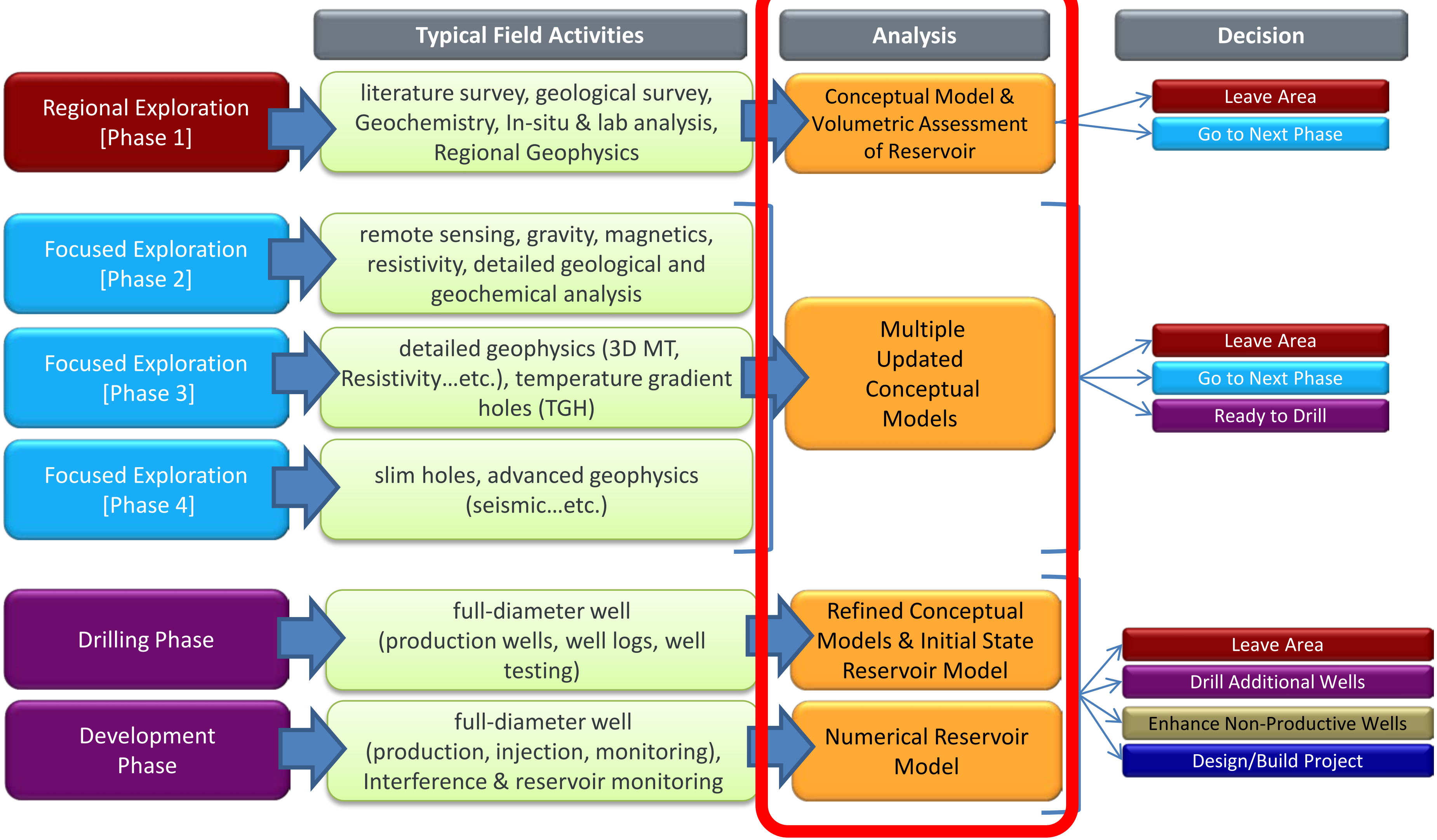

BACKGROUND

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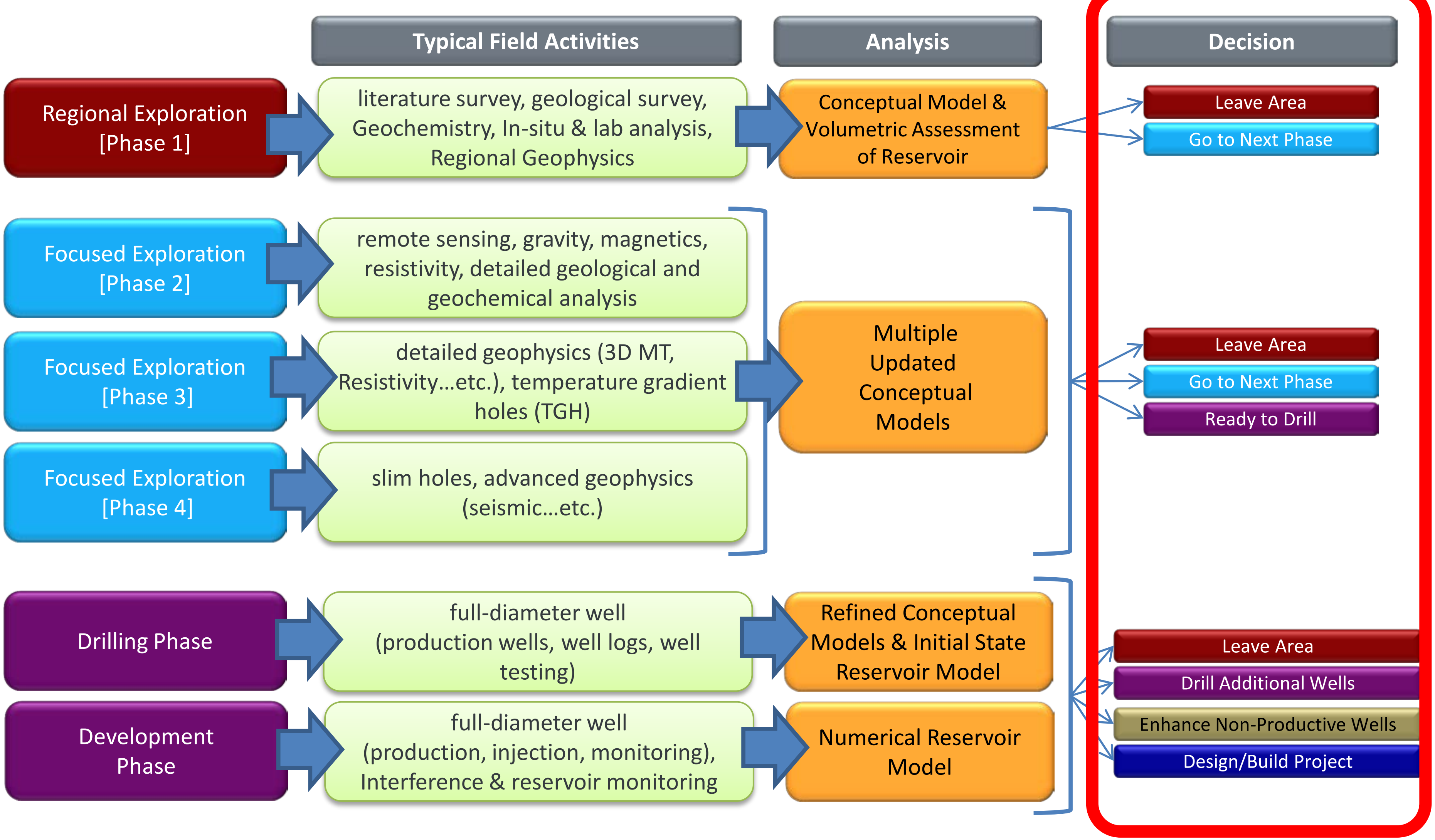


BACKGROUND

Uncertainty

We typically talk about uncertainty in terms of quality of data – how uncertain are the data based on the type of technique employed and the quality of the information?

Subjectivity

Refers to how someone's judgment is shaped by personal opinions and feelings instead of outside influences. Subjectivity negatively affects reproducibility.

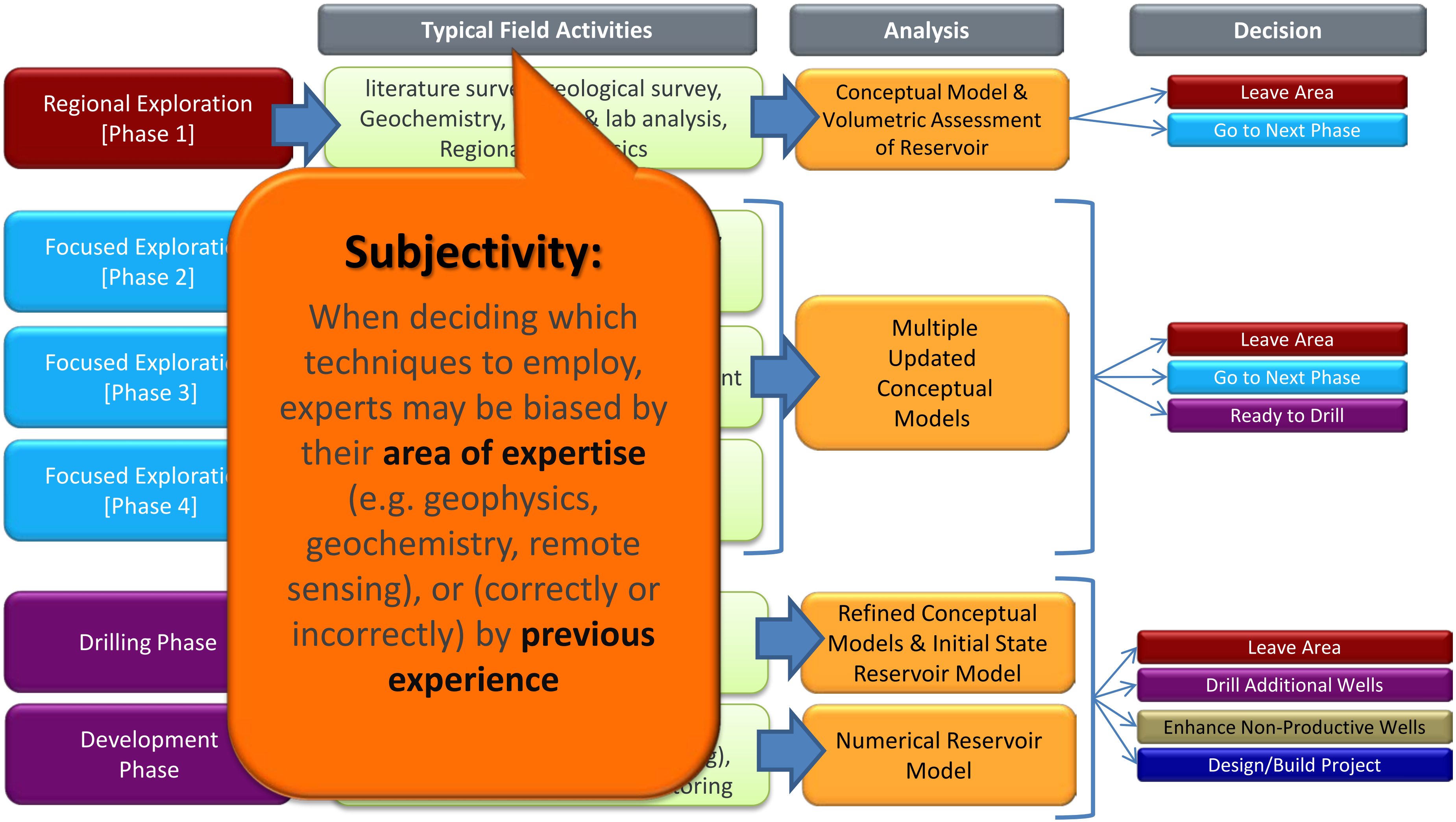
Reproducibility

Two experts could reproduce the same estimate (e.g., for temperature) with the same level of uncertainty, if methods are employed to reduce subjectivity.

Both **UNCERTAINTY** and **SUBJECTIVITY** contribute to project risk. We investigate methods that could be employed to reduce **SUBJECTIVITY** and increase **REPRODUCIBILITY.**

BACKGROUND

Subjectivity in the Exploration Process



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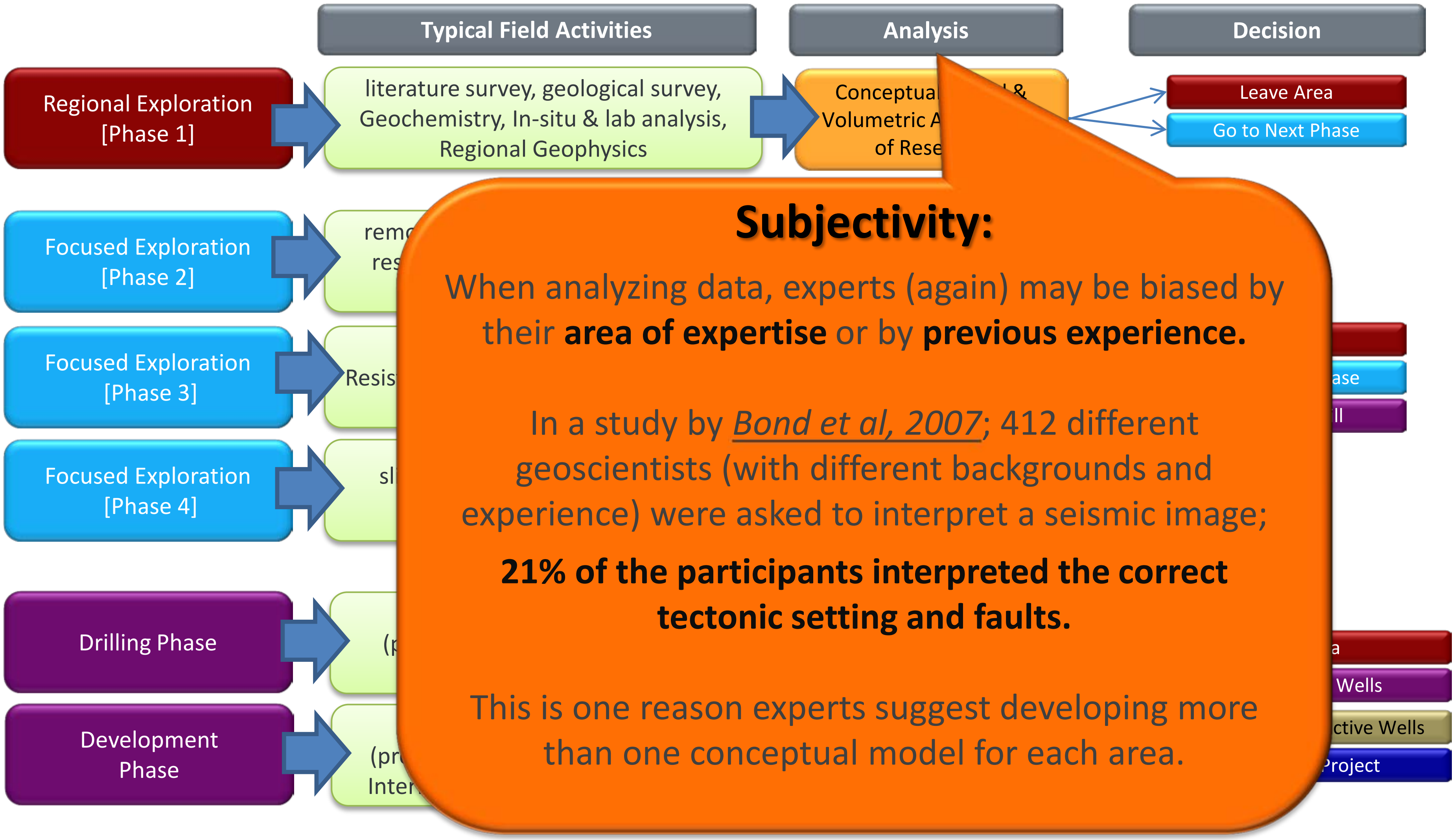
Subjectivity in the Exploration Process



Subjectivity:

When analyzing data, experts (again) may be biased by their **area of expertise** or by **previous experience.**

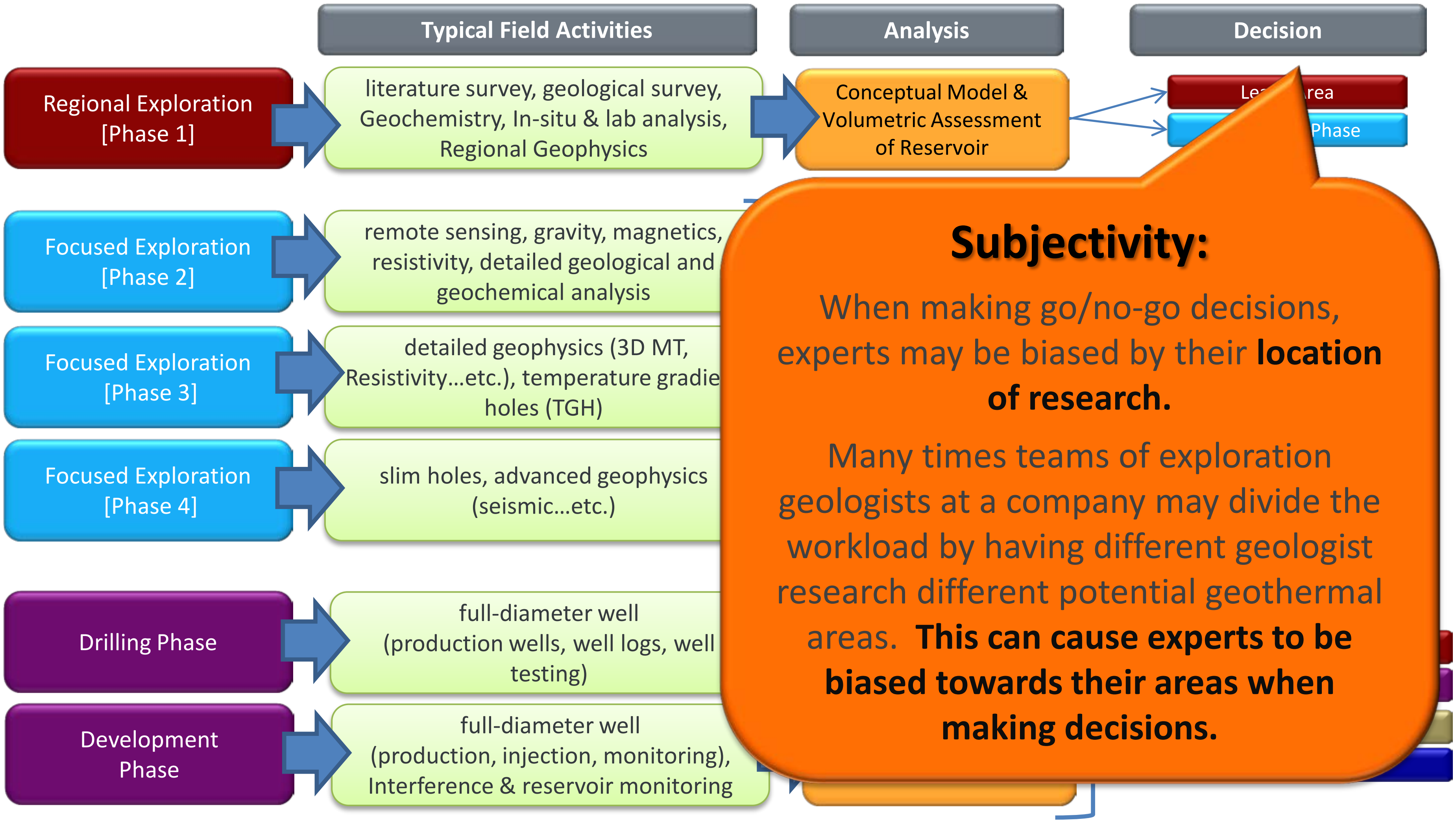
In a study by *Bond et al, 2007*; 412 different geoscientists (with different backgrounds and experience) were asked to interpret a seismic image;

21% of the participants interpreted the correct tectonic setting and faults.

This is one reason experts suggest developing more than one conceptual model for each area.

BACKGROUND

Subjectivity in the Exploration Process



Subjectivity:

When making go/no-go decisions, experts may be biased by their **location of research.**

Many times teams of exploration geologists at a company may divide the workload by having different geologist research different potential geothermal areas. **This can cause experts to be biased towards their areas when making decisions.**

BACKGROUND

Industry Request

In 2013, DOE and NREL led a series of Exploration Best Practice workshops.

Two questions were posed by industry during these workshops that prompted the current analysis:

1. **What is the best practice for making decisions during exploration?**

2. **What is a best practice for determining when to walk away at a given location?**

We will look at each of these questions in more detail, then discuss the reviewed methodology

METHOD 1

Value of Information Analysis

METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

1. What is the best practice for making decisions during exploration?

Experts gave examples where:

a. techniques were correctly implemented in the field, but was not necessarily useful in that particular geologic setting.

b. a technique was appropriate for the geologic setting, but wasn't correctly implemented – perhaps a survey line was laid out parallel to known linear features, rather than perpendicular to these features.

PROBLEM: The conducted activity did not improve the current understanding of the area (conceptual model)

METHODOLOGY REVIEWED: Value of Information Analysis (VOIA)

A VOIA attempts to identify the value of particular data in improving the reliability of the conceptual model before the exploration activity is conducted

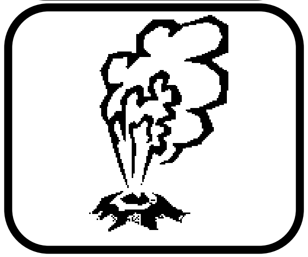
METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Previous Applications of VOIA

Medicine:
- Treatments for inhibitors of influenza
- Methods to shorten total hospital stay for acute cholecystitis
- *Wailoo et al., 2008; Wilson et al., 2010*

Civil Engineering:
- The impact of hazards on bridges structural safety *Straup, 2014*
- Grouting alternatives for tunnel construction *Zetterlung et al., 2011*

Oil & Gas:
- Value of 3D seismic data
- Well Log Information for identifying production zones.
- *Bratvold et al., 2009*

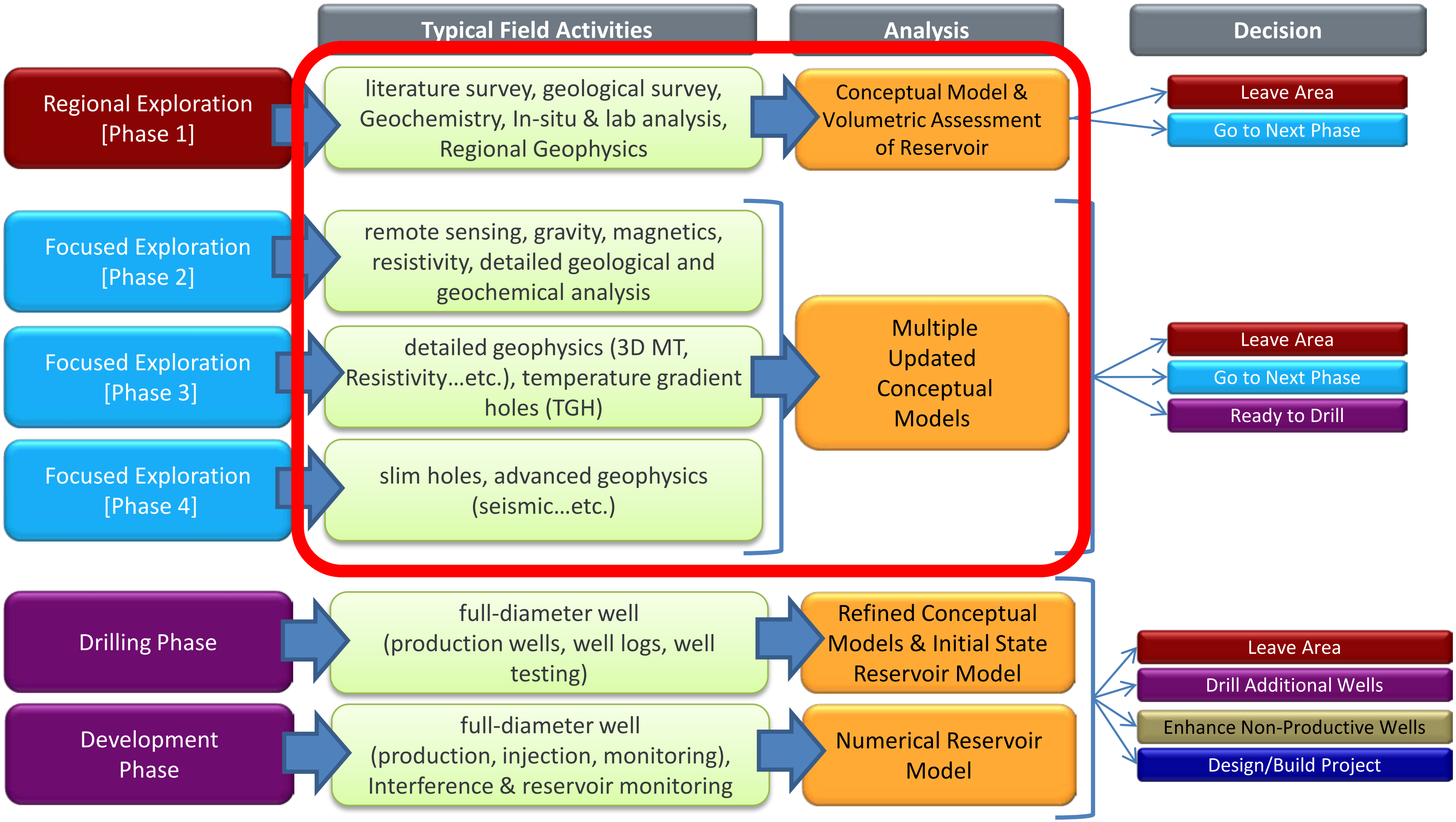


Geothermal:
- Value of 3D MT Data in identifying production well placement
- *Trainor-Guitton et al., 2013; Trainor-Guitton et al., 2014*

How could we expand the application of VOIA in geothermal to reduce subjectivity?

METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Target of VOIA Method



METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Potential Expansion of Use of VOIA

STEP 1:
Each version of each conceptual model will have two values to be estimated:

- Reliability of the model
- Value of risk

The project has an Expected Monetary Value (EMV) at the initial state.

$$EMV = Gain \times (R_M) - Loss \times (1-R_M)$$

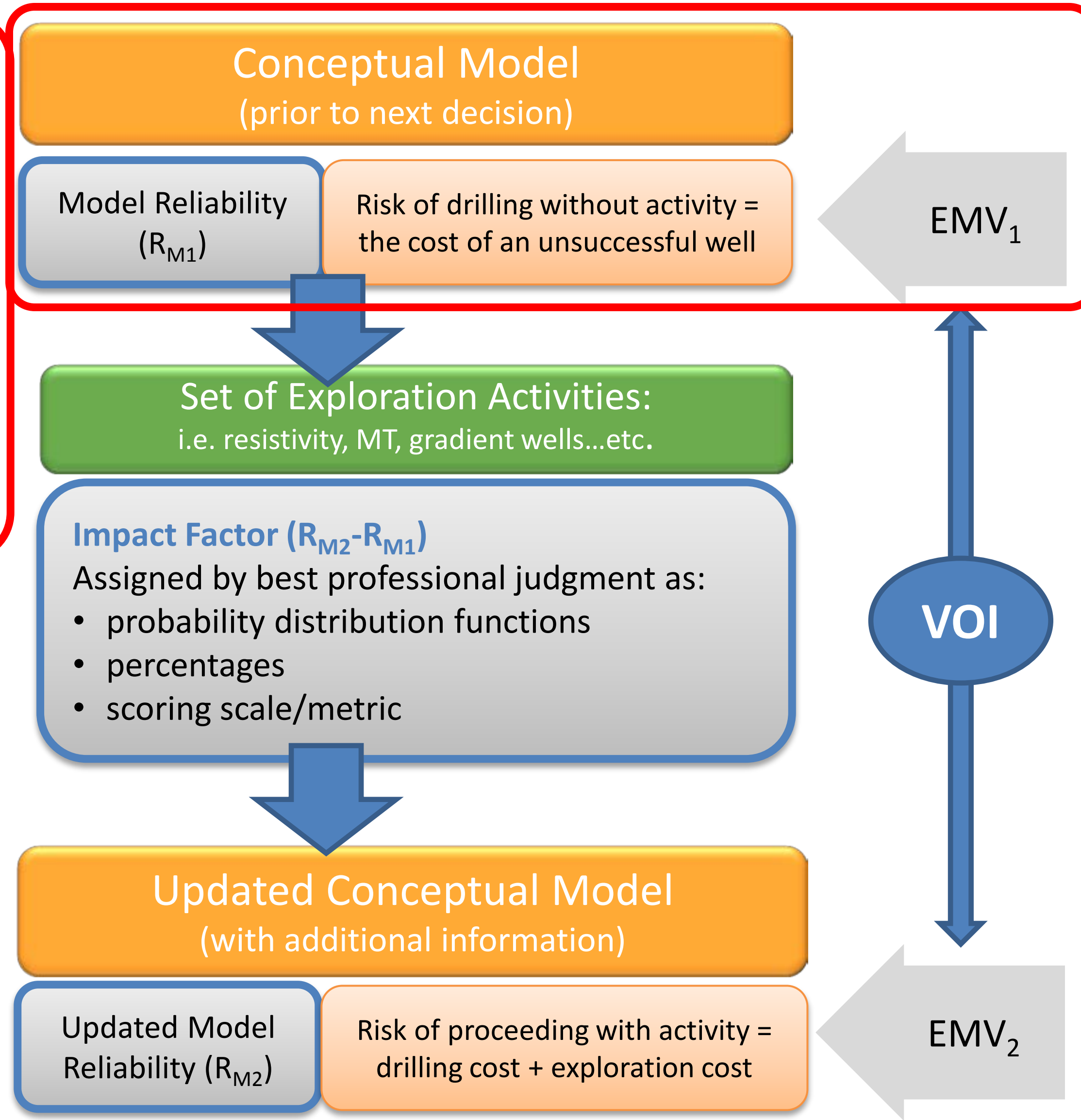
P: *Probability in model confidence/reliability*
Gain: *The Net Present Value (NPV) of the project*
Loss: *The value of risk*

STEP 2:
A potential activity (or set of activities) is evaluated and the impact factor is estimated

STEP 3:
The reliability of updated conceptual model, the value of risk, and EMV are estimated.

STEP 4:
The VOI can be calculated by calculating the difference between the two EMVs.

$$VOI = EMV_2 - EMV_1$$



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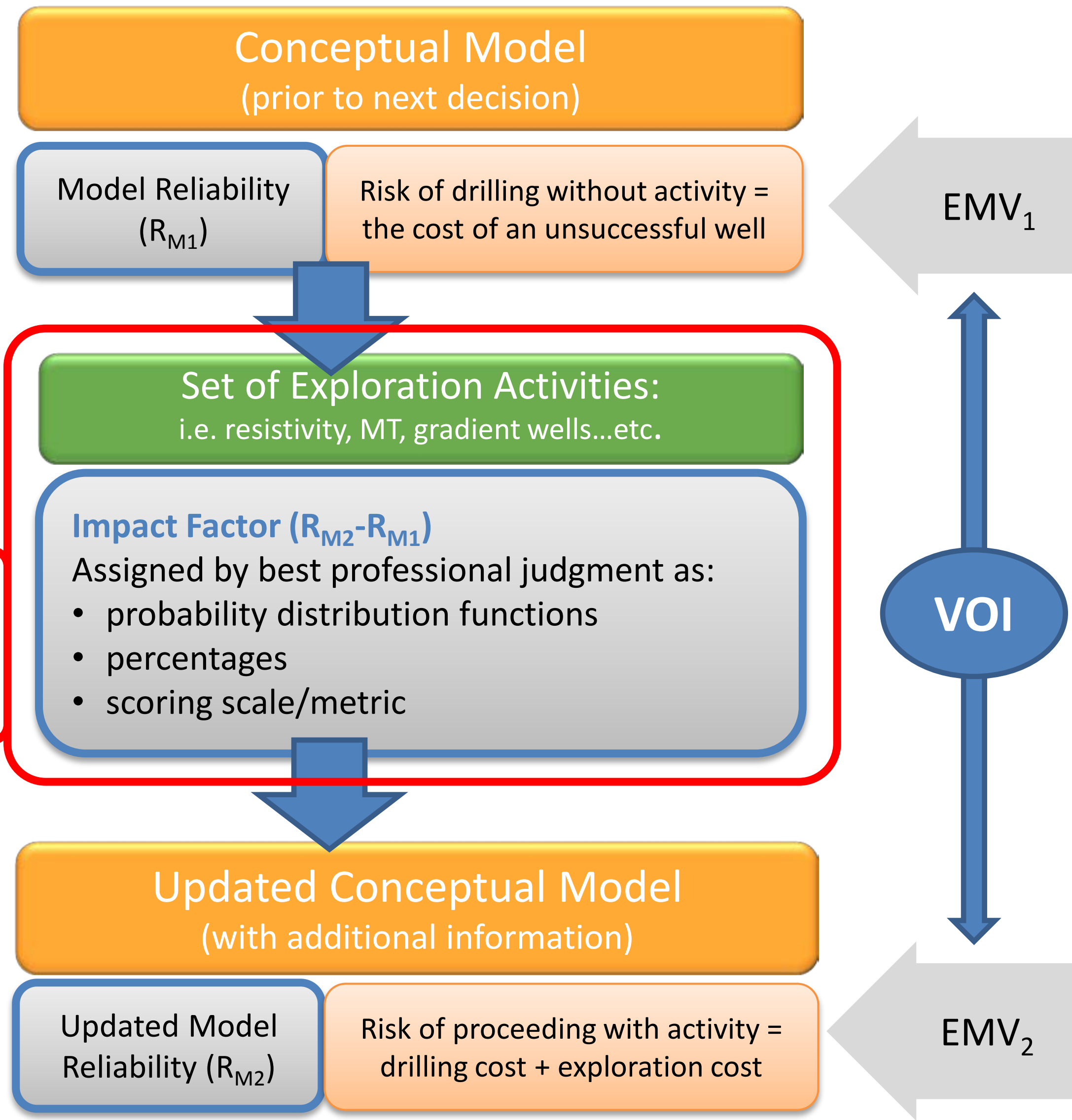

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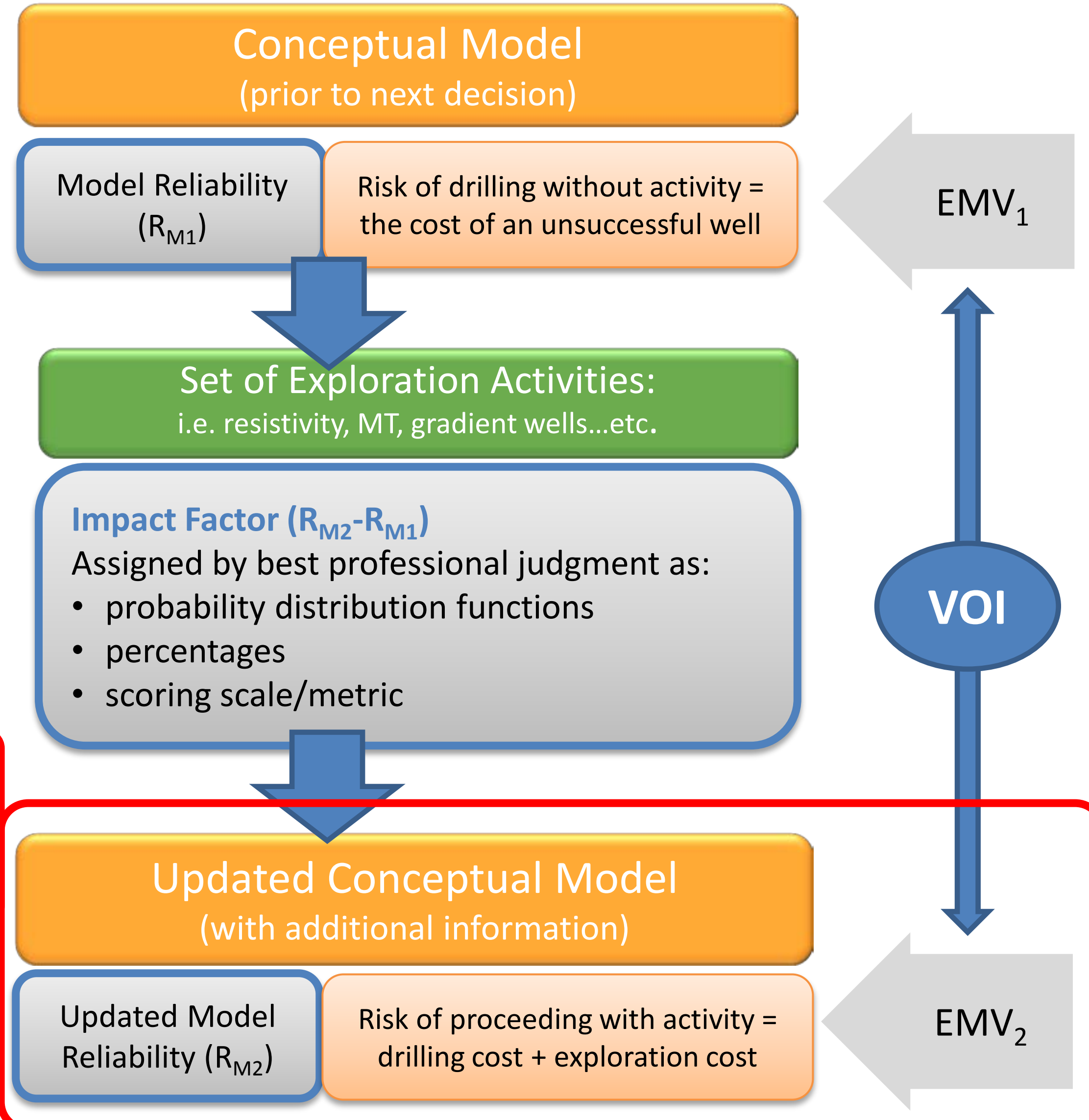

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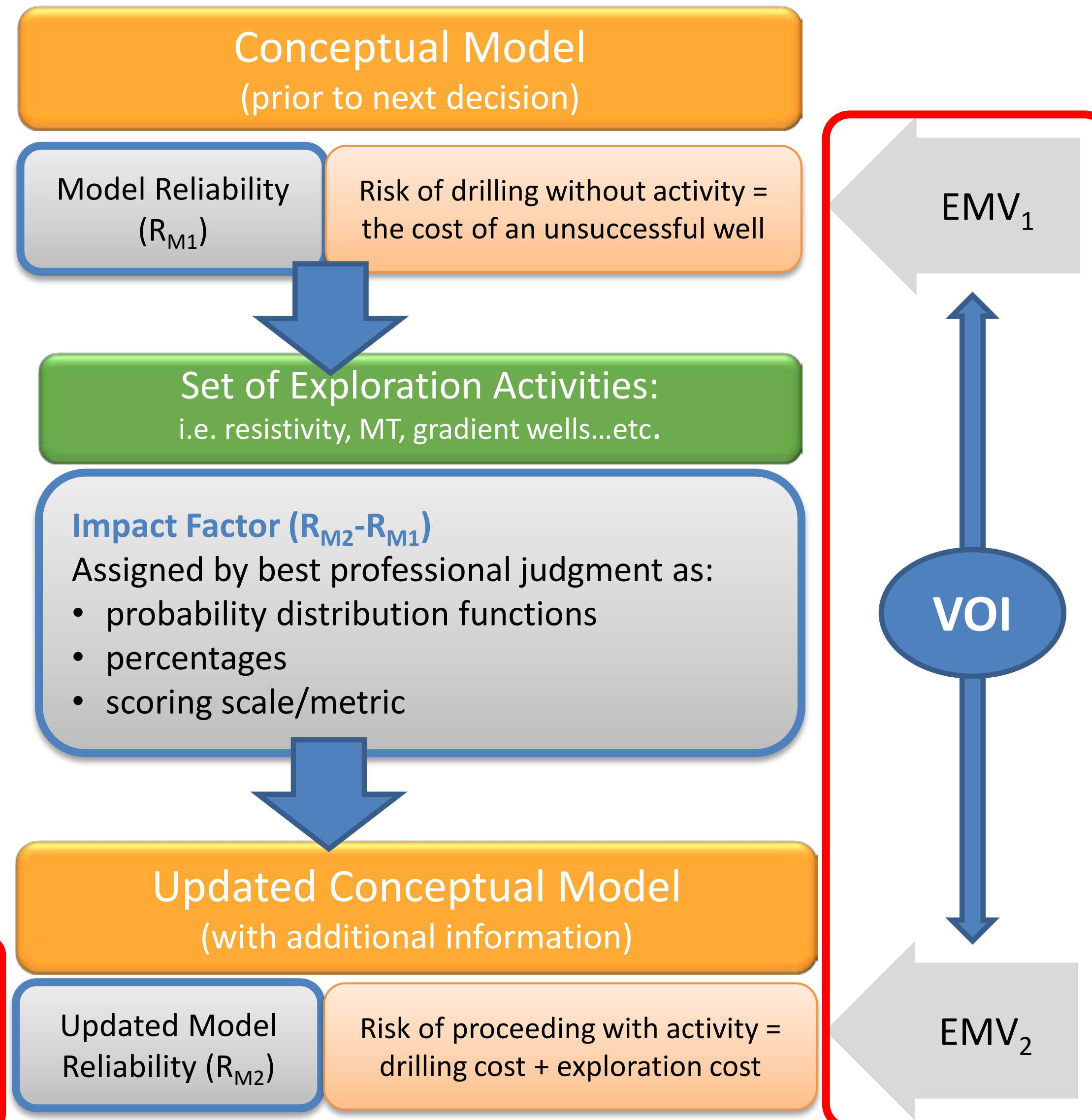

METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Potential Expansion of Use of VOIA

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EM

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STEP 2:
A potential a
evaluated an

STEP 3:
The reliability
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STEP 4:
The VOI can be calculated by calculating the difference between the two EMVs.

Conceptual Model
(prior to next decision)

Model Reliability

Risk of drilling without activity =

EMV_1

VOI

Updated Conceptual Model
(with additional information)

Updated Model Reliability (P_2)

Risk of proceeding with activity = drilling cost + exploration cost

EMV_2

If the estimated

Value of Information > Cost of Exploration Activities

then this methodology would suggest
you proceed with the proposed activity.

Note that the value of a particular set of information can be calculated to be insufficient or non-economic for a smaller project but may be economic when the project is larger.

METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Example:

Conceptual Model 1
(Model Reliability= 0.5)

+

Risk of Drilling
($4.25 million/well)

Net Present Value
($10 million/well)

Expected Monetary Value
($2.875 million)

+

Exploration Activities
e.g., 3D MT & TGH
(Impact Factor= 0.2)

Cost of Information
($1 million)

<

Value of Information
($2.55 million)

=

Conceptual Model 2
(Model Reliability= 0.7)

=

Risk of Drilling
($5.25 million/well)

Net Present Value
($10 million/well)

Expected Monetary Value
($5.425 million)

METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Potential Expansion of Use of VOIA

STEP 1:
Each version of each conceptual model will have two values to be estimated:
- Reliability of the model

Subjectivity:

In estimating:
- Development of **Conceptual Models** (as previously discussed)
- Estimating **Model Reliability** for each conceptual model, and
- Estimating **Impact Factor** for the set of exploration activities

STEP 4:
The VOI can be calculated by calculating the difference between the two EMVs.

Conceptual Model
(prior to next decision)

Model Reliability (R_{M1})

Risk of drilling without activity = the cost of an unsuccessful well

EMV_1

Set of Exploration Activities:
i.e. resistivity, MT, gradient wells…etc.

Impact Factor (R_{M2}-R_{M1})
Assigned by best professional judgment as:
- probability distribution functions
- percentages
- scoring scale/metric

VOI

Updated Conceptual Model
(with additional information)

Updated Model Reliability (R_{M2})

Risk of proceeding with activity = drilling cost + exploration cost

EMV_2

METHOD: VALUE OF INFORMATION ANALYSIS (VOIA)

Additional Work to be Done

Work to reduce subjectivity and increase reproducibility. Two potential ways the level of subjectivity can be reduced include:

- Developing some sort of **scoring scale/metric** with specific criteria to replace estimated probabilities
- Using **historical data statistics** collected from analogous **geological settings and geothermal play types.**

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METHOD 2

Exploration
Targeting
Analysis

METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

2. What is a best practice for determining when to walk away at a given location?

Anecdotal quotes:

a. “If we just do xxx, then we’ll know our field know where to drill.”

b. “no well is ever unsuccessful because it gives us more data and helps us to improve our conceptual model”

c. “We can still produce power from this field.”

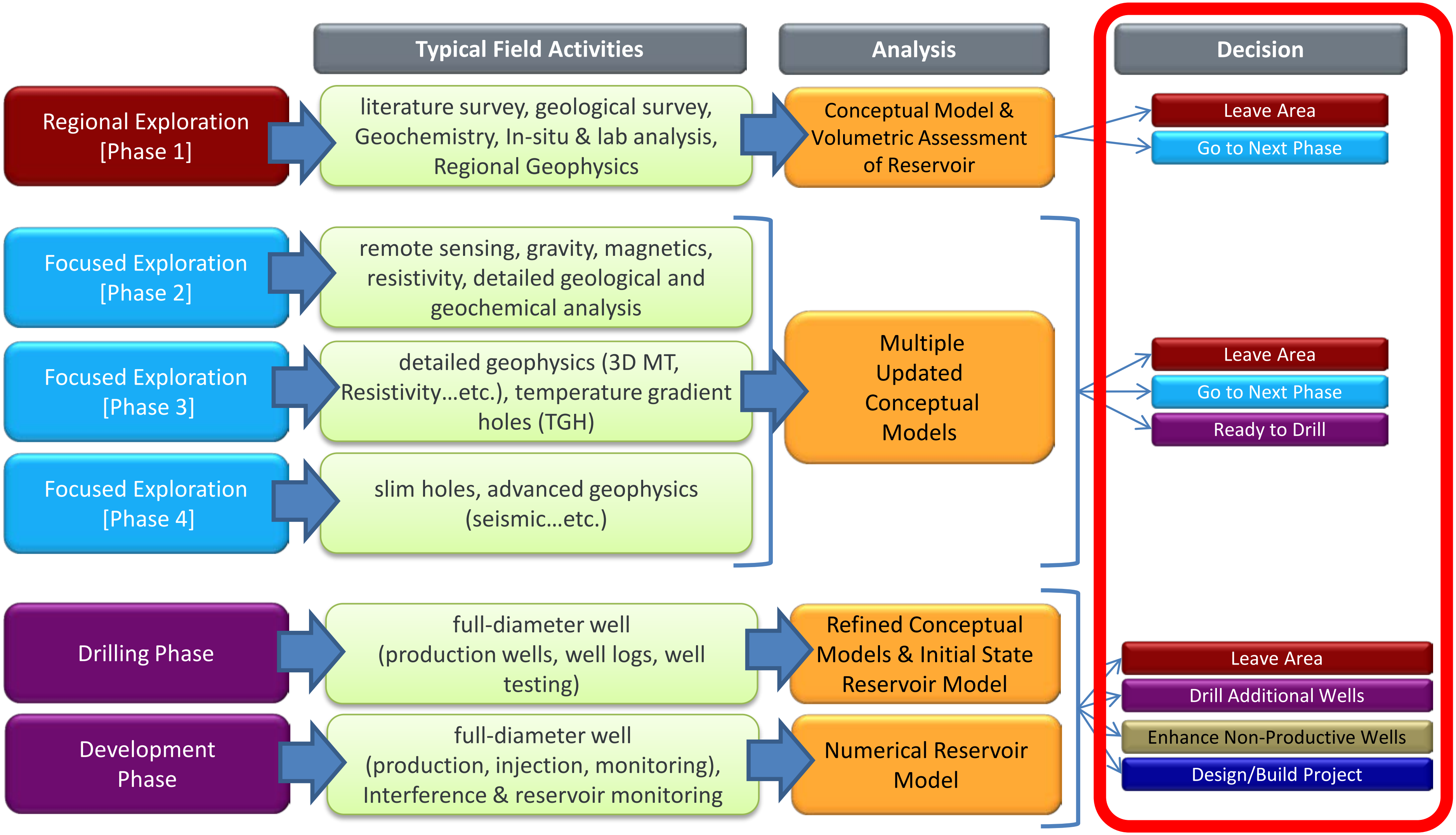
PROBLEM: How do you objectively determine when to walk away from a field?

METHODOLOGY REVIEWED: Exploration Targeting based on IRR limits

The Exploration Targeting Analysis (ETA) sets a minimum Internal Rate of Return (IRR) to define minimum required exploration targets.

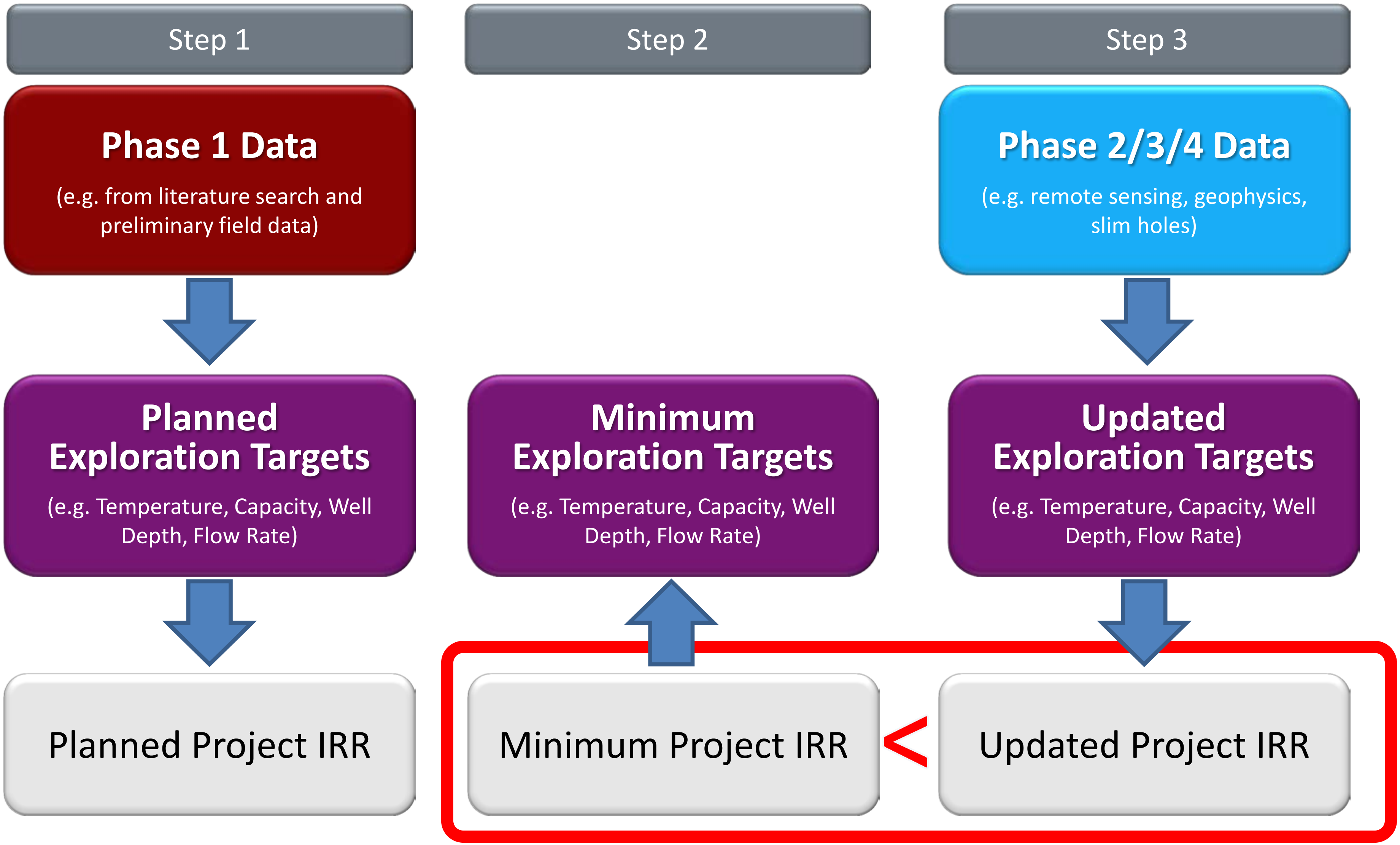
METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

Target of ETA



METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

Overview



METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

Potential Application of ETA

		Phase 1	
	Units	Target	Go-No/Go
Minimum Desired IRR	%	17.0%	**13.0%**
Calculated IRR		17.1%	13.1%
Inputs			
Installed Power	MWe	30	12
Reservoir Temperature	°C	192	160
Min. Ave. Temperature Gradient	°C/100m	9.00	7.50
Min. Re-Injection Temperature	°C	70	70
Average Target Capacity per Well	MWe/well	4.5	3.0
Maximum Exploration Budget	$	5,000,000	3,000,000
Assumptions			
Project Lifetime	years	25	25
Project Completion Time	years	5	5
Utilization Factor	%	0.95	0.95
Pump cost	$/per well	0	500,000
Effective Sales Price (PPA or FIT)	cents/kWh	10.5	10.5
Power Plant (EM) Cost	$/MWe	1,500,000	1,500,000
Power Plant (O&M) Cost	$/MWh	9.00	10.00
Financial Contingency	%	8%	8%
Conversion Constant	kCal/kWh	860	860
Specific Heat	kCal/kg°C	1	1
Density	kg/m³	998.15	998.15
Exploration Targets			
Number of Production Wells	#	7.0	4.0
Number of Re-Injection Wells	#	3.0	2.0
Max Drilling Budget per Well		4,551,115	4,551,115
Well Testing	$	1,750,000	1,000,000
Maximum Total Drilling Budget	$	45,511,154	27,306,692
Target Well Depth	m	2,133	2,133
Required Total Flow Rate	L/s	562	343

STEP 1:
Use data collected in Phase 1 of exploration to make initial estimate of IRR. Exploration Targets are calculated based on Inputs and Assumptions

Note that there is uncertainty involved in the estimates entered in this table. Monte Carlo analyses are often used in these calculations to be able to capture uncertainty. Because uncertainty is not the focus of our analysis, we simplify the model here for illustration purposes.

STEP 2:
Using a minimum IRR, develop a scenario using the available input values – can a plausible scenario be developed at the target IRR? New

Note that there is not one right answer here, since all of the input variables are dependent upon each other.

STEP 3: (not shown)
For each successive phase of exploration, continue to update inputs, making sure to stay within the target IRR

METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

Potential Application of ETA

		Phase 1	
	Units	Target	Go-No/Go
Minimum Desired IRR	%	[illegible]	**13.0%**
Calculated IRR	%	17.1%	13.1%
Inputs			
Installed Power	MWe	30	12
Reservoir Temperature	°C	192	160
Min. Ave. Temperature Gradient	°C/100m	[illegible]	7.50
Min. Re-Injection Temperature	°C	70	70
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METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

Potential Application of ETA

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	Units	Target	Go-No/Go
Minimum Desired IRR	%	17.0%	**13.0%**
Calculated IRR	%	17.1%	13.1%
Inputs			
Installed Power	*MWe*	30	12
Reservoir Temperature	*°C*	192	160
Min. Ave. Temperature Gradient	*°C/100m*	9.00	7.50
Min. Re-Injection Temperature	*°C*	70	70
Average Target Capacity per Well	*MWe/well*	4.5	3.0
Maximum Exploration Budget	*$*	5,000,000	3,000,000
Assumptions			
Project Lifetime	*years*	25	25
Project Completion Time	*years*	5	5
Utilization Factor	*%*	0.95	0.95
Pump cost	*$/per well*	0	500,000
Effective Sales Price (PPA or FIT)	*cents/kWh*	10.5	10.5
Power Plant (EM) Cost	*$/MWe*	1,500,000	1,500,000
Power Plant (O&M) Cost	*$/MWh*	9.00	10.00
Financial Contingency	*%*	8%	8%
Conversion Constant	*kCal/kWh*	860	860
Specific Heat	*kCal/kg°C*	1	1
Density	*kg/m^3*	998.15	998.15
Exploration Targets			
Number of Production Wells	*#*	7.0	4.0
Number of Re-Injection Wells	*#*	3.0	2.0
Max Drilling Budget per Well	*$*	4,551,115	4,551,115
Well Testing	*$*	1,750,000	1,000,000
Maximum Total Drilling Budget	*$*	45,511,154	27,306,692
Target Well Depth	*m*	2,133	2,133
Required Total Flow Rate	*L/s*	562	343

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METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

		Phase 1	
	Units	Target	Go-No/Go
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Calculated IRR	%	17.1%	13.1%
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Reservoir Temperature	°C	192	160
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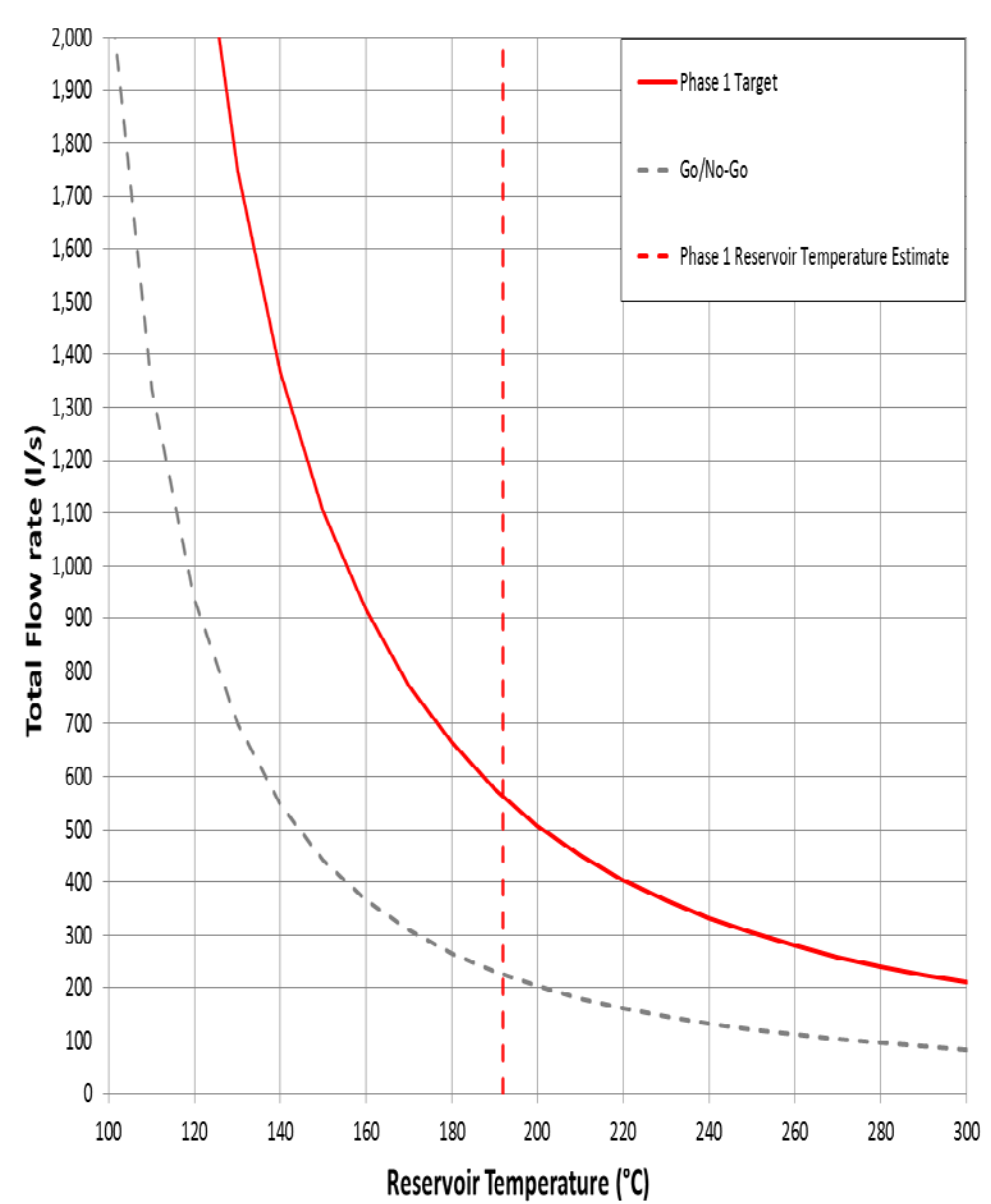
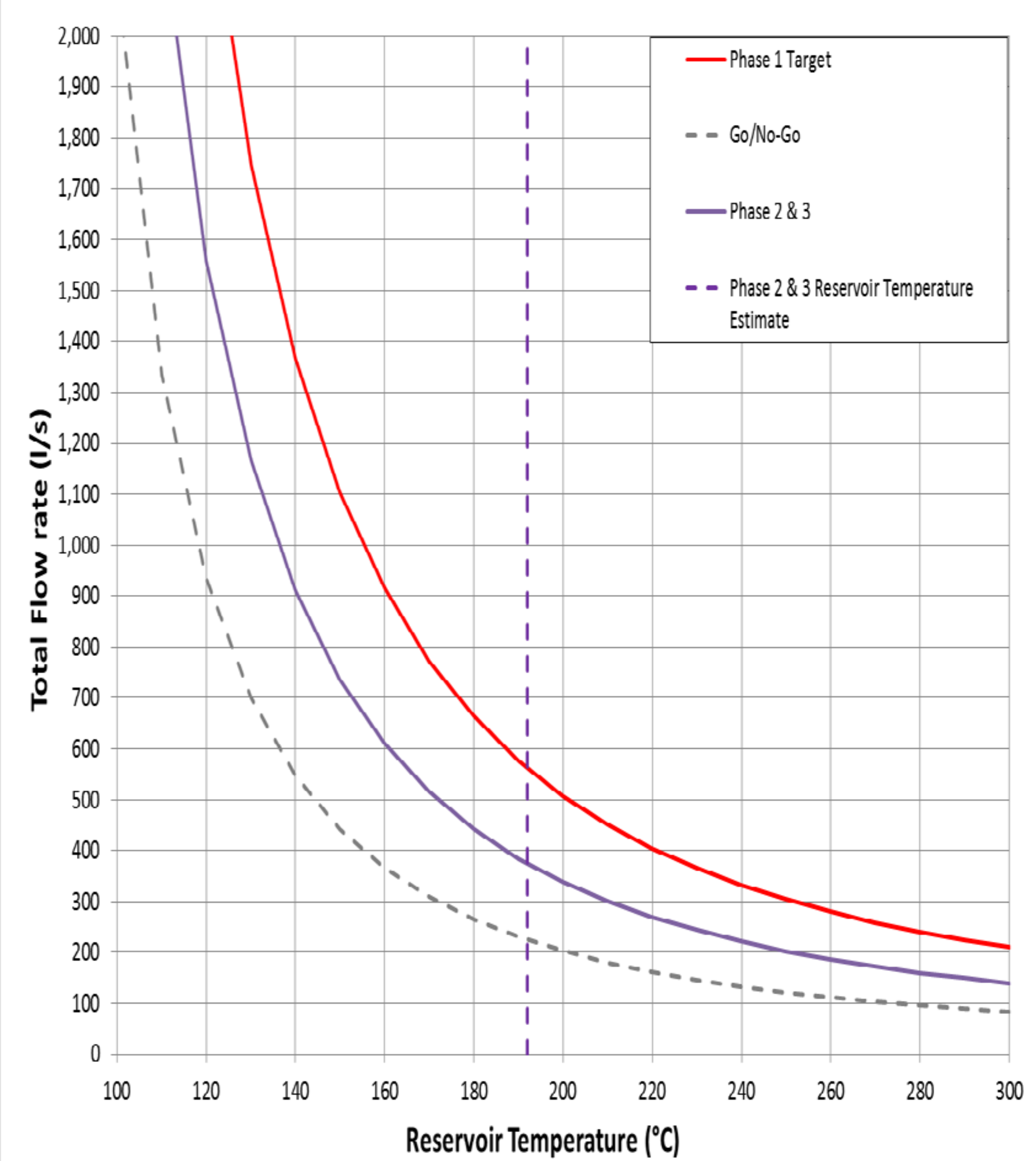
Well Testing	$	1,750,000	1,000,000
Maximum Total Drilling Budget	$	45,511,154	27,306,692
Target Well Depth	m	2,133	2,133
Required Total Flow Rate	L/s	562	343



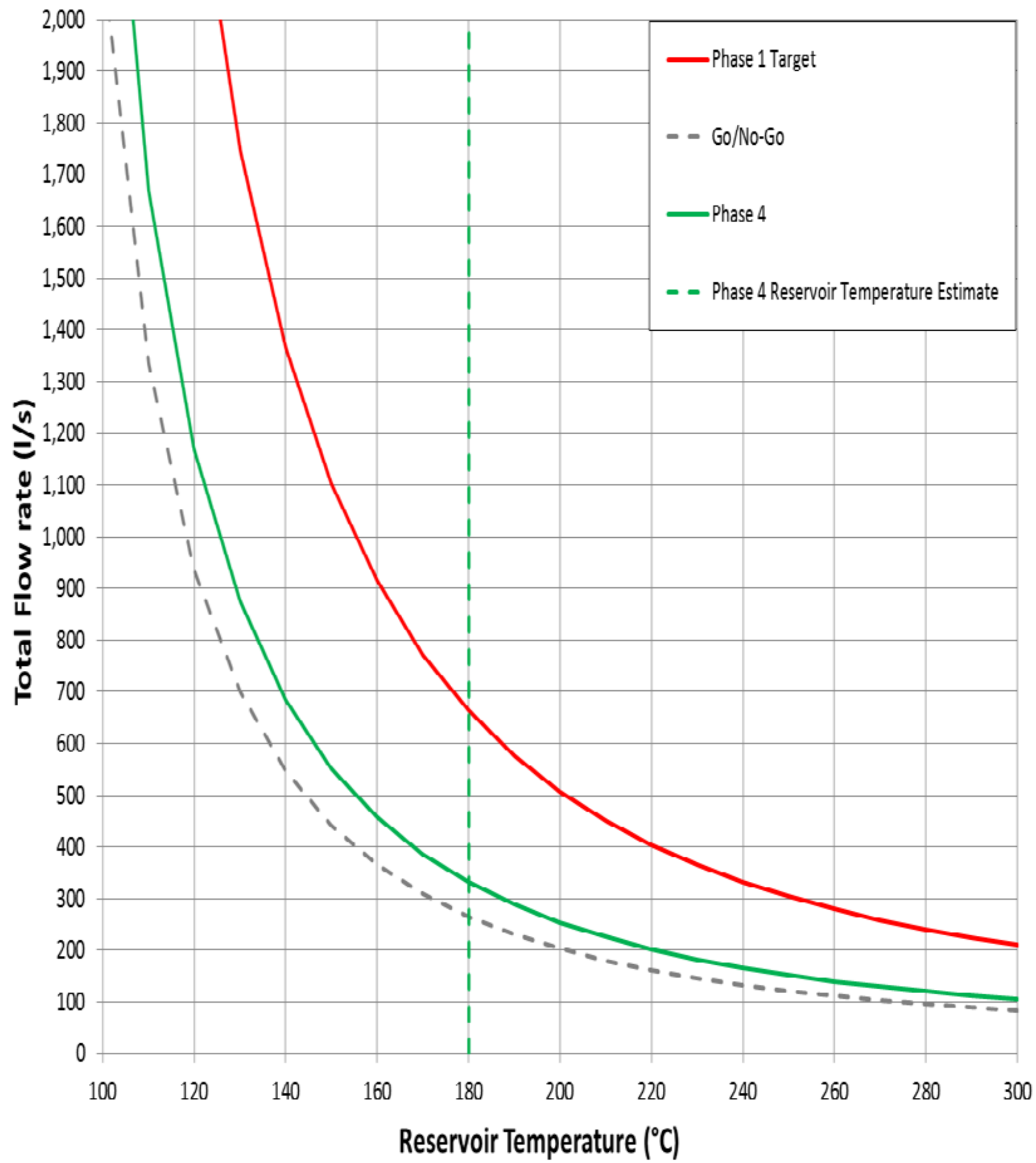
METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

		Phase 2 & 3
	Units	Actual
Minimum Desired IRR	%	-
Calculated IRR	%	16.2%
Inputs		
Installed Power	MWe	20
Reservoir Temperature	°C	192
Min. Ave. Temperature Gradient	°C/100m	9.00
Min. Re-Injection Temperature	°C	70
Average Target Capacity per Well	MWe/well	4.0
Maximum Exploration Budget	$	5,000,000
Assumptions		
Project Lifetime	years	25
Project Completion Time	years	5
Utilization Factor	%	0.95
Pump cost	$/per well	0
Effective Sales Price (PPA or FIT)	cents/kWh	10.5
Power Plant (EM) Cost	$/MWe	1,500,000
Power Plant (O&M) Cost	$/MWh	9.00
Financial Contingency	%	8%
Conversion Constant	kCal/kWh	860
Specific Heat	kCal/kg°C	1
Density	kg/m³	998.15
Exploration Targets		
Number of Production Wells	#	5.0
Number of Re-Injection Wells	#	2.0
Max Drilling Budget per Well	$	4,551,115
Well Testing	$	1,250,000
Maximum Total Drilling Budget	$	31,857,808
Target Well Depth	m	2,133
Required Total Flow Rate	L/s	375



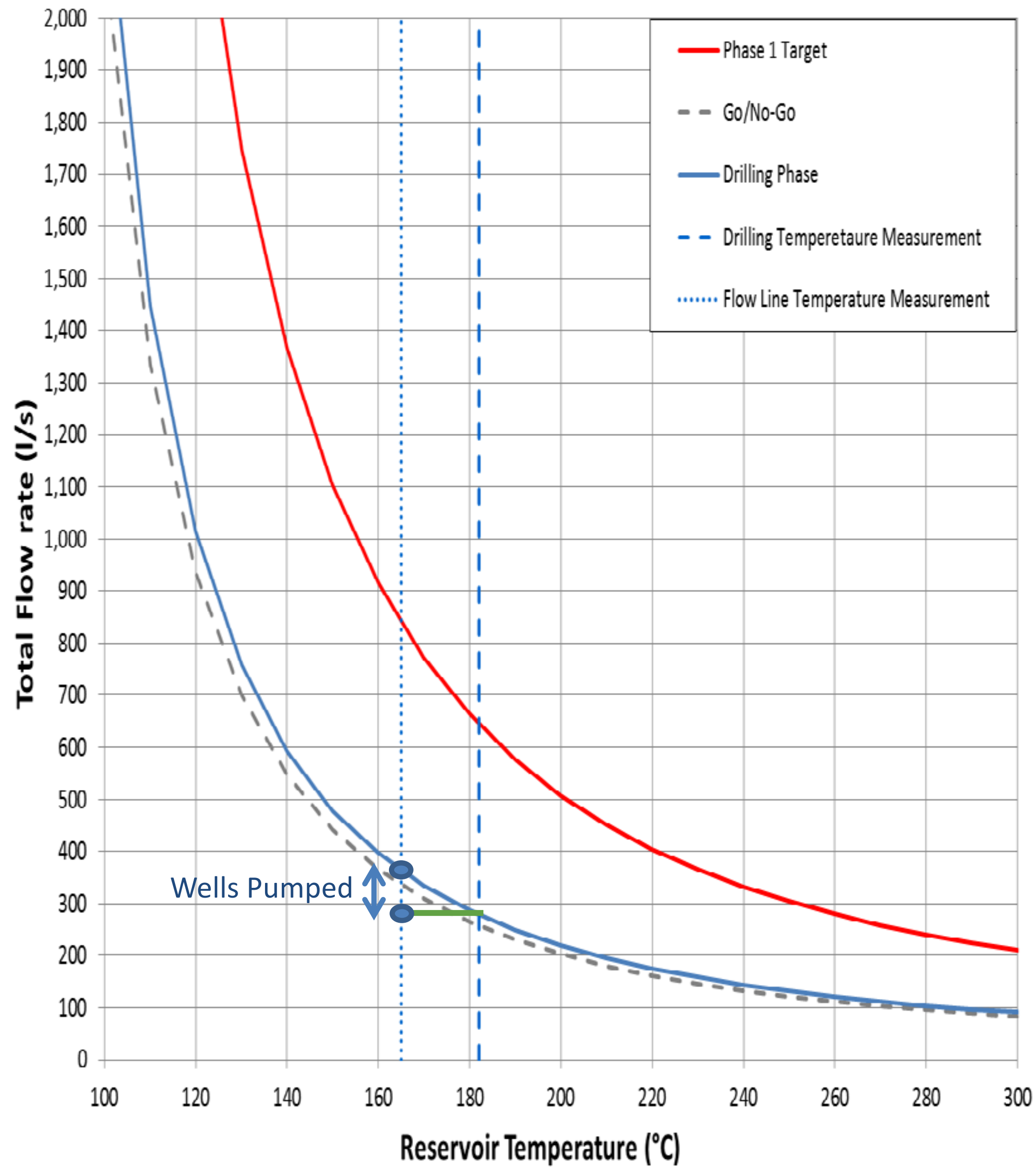
METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

	Units	Phase 4 Actual
Minimum Desired IRR	%	-
Calculated IRR	%	14.3%
Inputs		
Installed Power	MWe	15
Reservoir Temperature	°C	180
Min. Ave. Temperature Gradient	°C/100m	8.00
Min. Re-Injection Temperature	°C	70
Average Target Capacity per Well	MWe/well	4.0
Maximum Exploration Budget	$	3,000,000
Assumptions		
Project Lifetime	years	25
Project Completion Time	years	5
Utilization Factor	%	0.95
Pump cost	$/per well	0
Effective Sales Price (PPA or FIT)	cents/kWh	10.5
Power Plant (EM) Cost	$/MWe	1,500,000
Power Plant (O&M) Cost	$/MWh	9.00
Financial Contingency	%	8%
Conversion Constant	kCal/kWh	860
Specific Heat	kCal/kg°C	1
Density	kg/m³	998.15
Exploration Targets		
Number of Production Wells	#	4.0
Number of Re-Injection Wells	#	2.0
Max Drilling Budget per Well	$	5,062,505
Well Testing	$	1,000,000
Maximum Total Drilling Budget	$	30,375,027
Target Well Depth	m	2,250
Required Total Flow Rate	L/s	332



METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

	Units	Drilling Actual
Minimum Desired IRR	%	-
Calculated IRR	%	13.7%
Inputs		
Installed Power	*MWe*	13
Reservoir Temperature	*°C*	182
Min. Ave. Temperature Gradient	*°C/100m*	8.50
Min. Re-Injection Temperature	*°C*	70
Average Target Capacity per Well	*MWe/well*	3.5
Maximum Exploration Budget	*$*	3,000,000
Assumptions		
Project Lifetime	*years*	25
Project Completion Time	*years*	5
Utilization Factor	*%*	0.95
Pump cost	*$/per well*	500,000
Effective Sales Price (PPA or FIT)	*cents/kWh*	10.5
Power Plant (EM) Cost	*$/MWe*	1,500,000
Power Plant (O&M) Cost	*$/MWh*	10.00
Financial Contingency	*%*	8%
Conversion Constant	*kCal/kWh*	860
Specific Heat	*kCal/kg°C*	1
Density	*kg/m³*	998.15
Exploration Targets		
Number of Production Wells	*#*	4.0
Number of Re-Injection Wells	*#*	2.0
Max Drilling Budget per Well	*$*	4,584,641
Well Testing	*$*	1,000,000
Maximum Total Drilling Budget	*$*	27,507,846
Target Well Depth	*m*	2,141
Required Total Flow Rate	*L/s*	279



METHOD: EXPLORATION TARGETING ANALYSIS (ETA)

Additional Work to be Done

The initial model built for this analysis was intentionally simple. Additional complexity can be added to the model for actual use in the field. For example:

- The input variables used in the model is not always a definite number and may have a range of value. In this case **Monte Carlo simulation** can be used to reduce the assign input variables while calculating the heat in place and production capacity of the reservoir.
- In the exploration targeting model, energy conversion calculations are based on an average enthalpy value and single-phase flow. **Enthalpy calculations** may be different in a double-phase flow having different brine-gas ratio.
- **The financial model** used in ETA assumes 100% equity financing with a certain percentage of financial contingency. A detailed financial model can be included in the model with variables and parameters from debt financing.

DISCUSSION

METHOD: Value of Information Analysis (VOIA)

Helps to justify the cost of additional exploration activities by showing impact to understanding of area geology (reliability of conceptual model)

- This initial work shows that VOIA has a high degree of subjectivity in assigning probabilities.
- The level of subjectivity can be decreased by;
  - using historical data statistics collected from analogous geological settings and geothermal play types
  - assigning impact buckets or reliability percentages
- VOIA approach is sensitive to project capacity. Consequently, a set of exploration activities may have higher VOI for larger capacity projects while they are not found to be economic to purchase for smaller size projects.

METHOD: Exploration Targeting Analysis (ETA)

Helps to facilitate communication between project managers and exploration geologists in making objective go/no-go decisions throughout the different project phases

- Exploration targeting approach is appears to be less subjective and more reproducible because numerical inputs come from collected data (but still has significant uncertainty).

This project is funded by the Geothermal Technologies Office through Annual Operating Plan funds.

Thank You

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Acknowledgments:
This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory (NREL). The authors wish to thank reviewers for their comments and suggestions including Chad Augustine, Emily Newes, Tom Williams, and David Mooney. In addition, we also wish to thank Kendra Palmer (NREL) for her technical review. All errors and omissions are the responsibility of the authors