Professional Development Workshop on

Critical Raw Materials Content in Thermal Waters: Analysis and Assessment

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University of Miskolc, Hungary

Geological risk assessment in geothermal developments: how and why?

Thought Experiment

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BRINE RIS

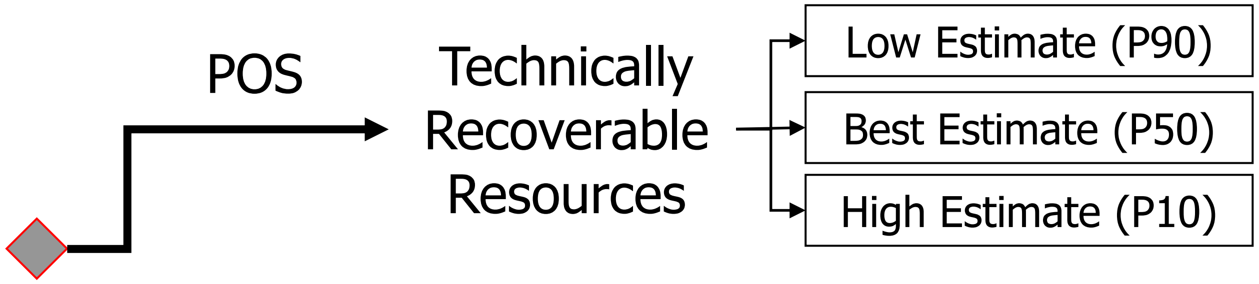
GEOLOGICAL RISK – GEOLOGICAL PROBABILITY

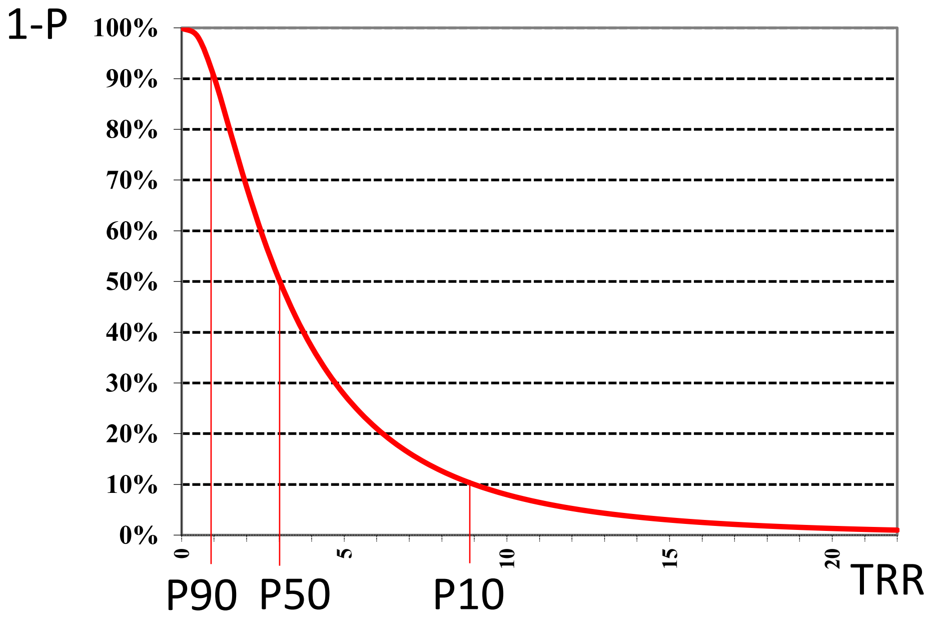
What is Geological Risk?

- Project fails due to unfavorable geological (non-technical) conditions
- Probability of the adverse outcome of stochastic geological events

Geological Probability – Probability of Success (POS) – Oil & gas exploration

- Geological chance for Project success – Discovery of recoverable hydrocarbons
- 1-POS (Geological Risk): Chance for a dry well – Expenditures lost (Dry Hole Cost)





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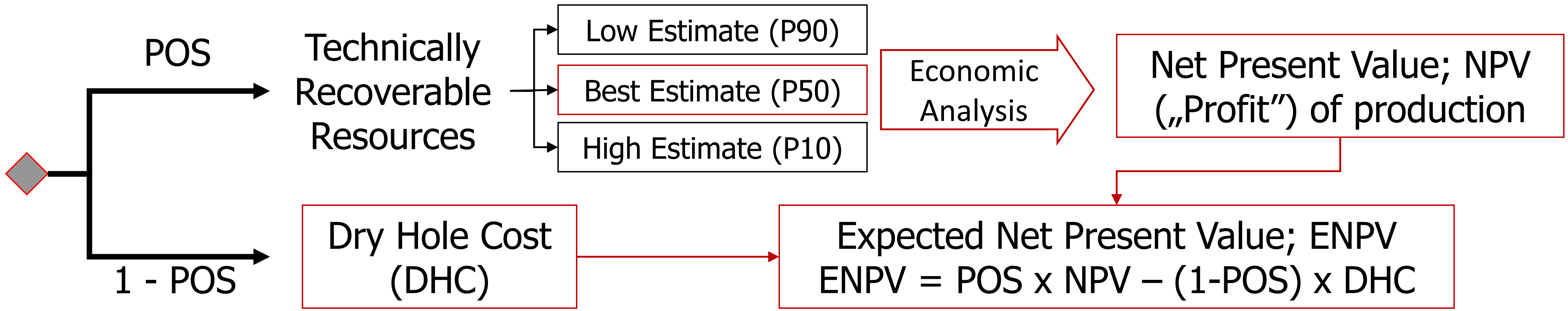
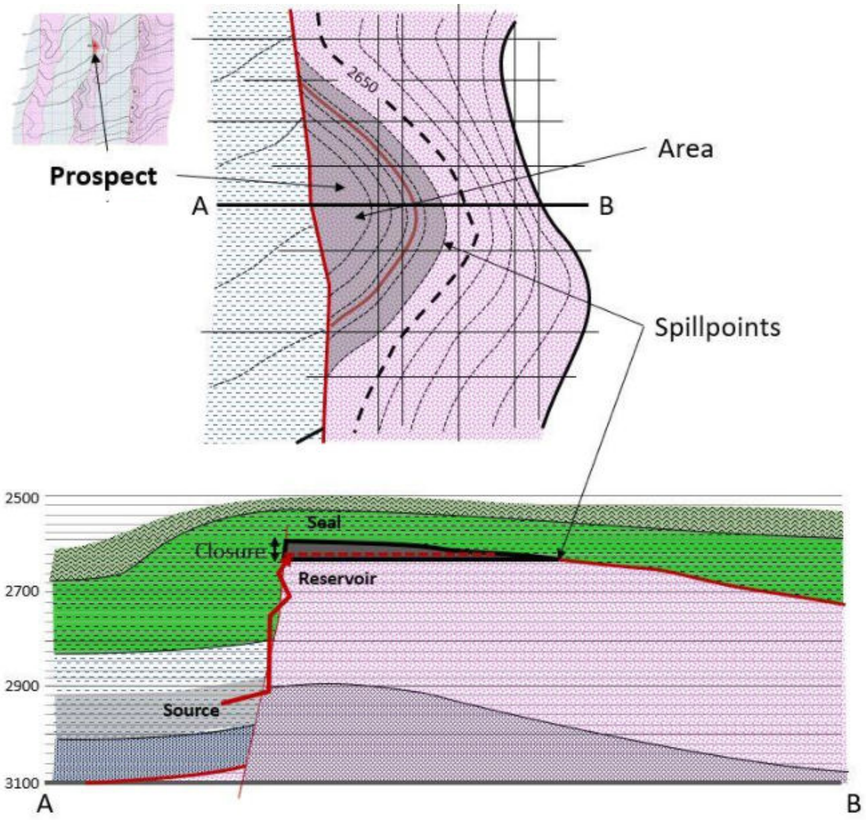
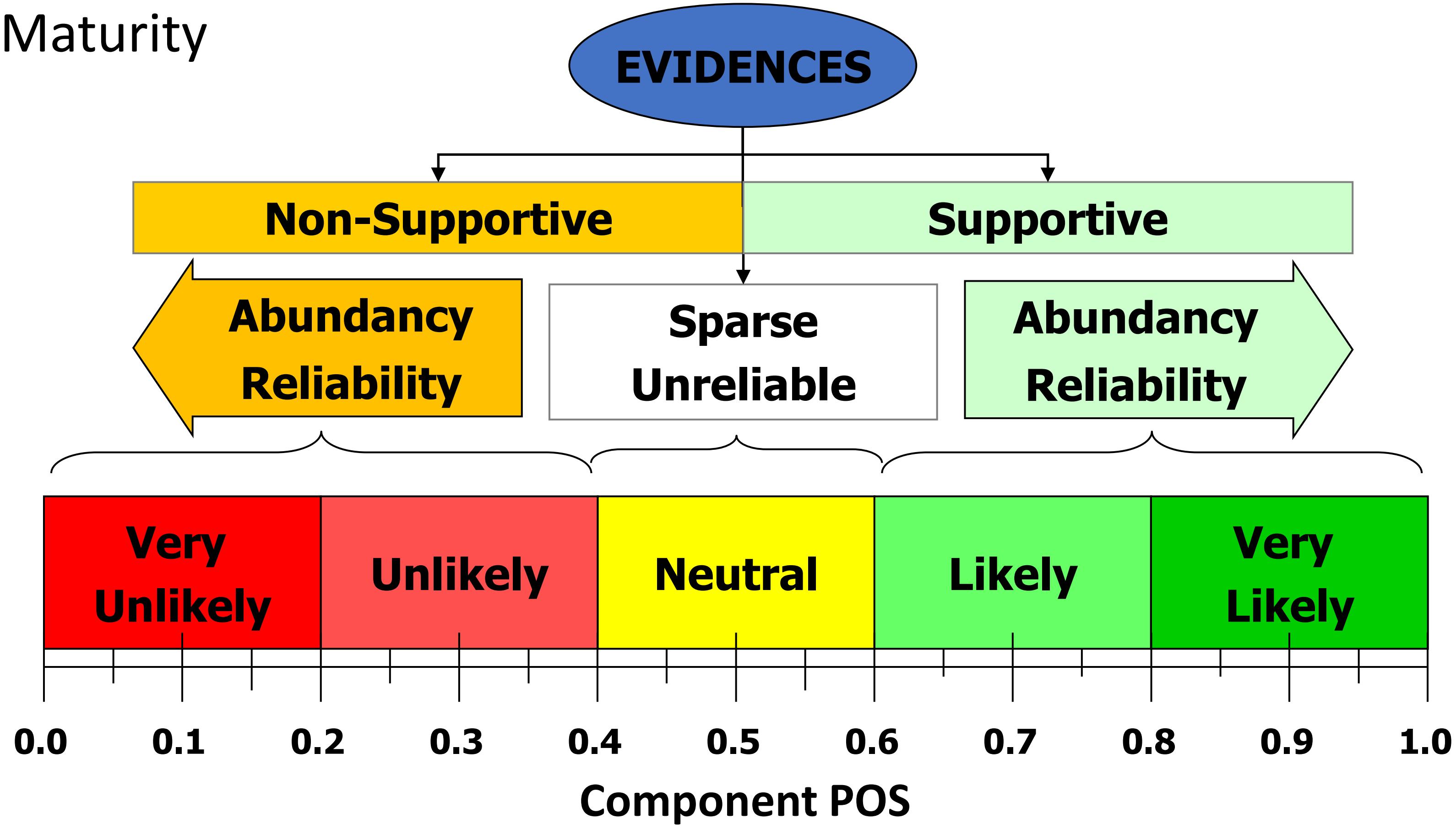


- If ENPV > 0: Well is drilled
- If ENPV < 0; Well is not drilled

POS QUANTIFICATION IN HYDROCARBON EXPLORATION

- Source Rock, Migration, Reservoir, Seal & Trap Developments are POS Components
- POS for each Component is quantified by data and interpretations as evidences
- Supportiveness & Exploration Maturity





$$POS_{prospect} = POS_{source} \times POS_{migration} \times POS_{reservoir} \times POS_{seal} \times POS_{trap}$$

GEOLOGICAL RISK/PROBABILITY IN GEOTHERMAL

Why can geothermal developments fail?

- Technical failures – Drilling problems
- Project management failures – Poor planning and control
- Geological failures – Undervaluation of geological risk factors

Geothermal Probability of Success (POS)

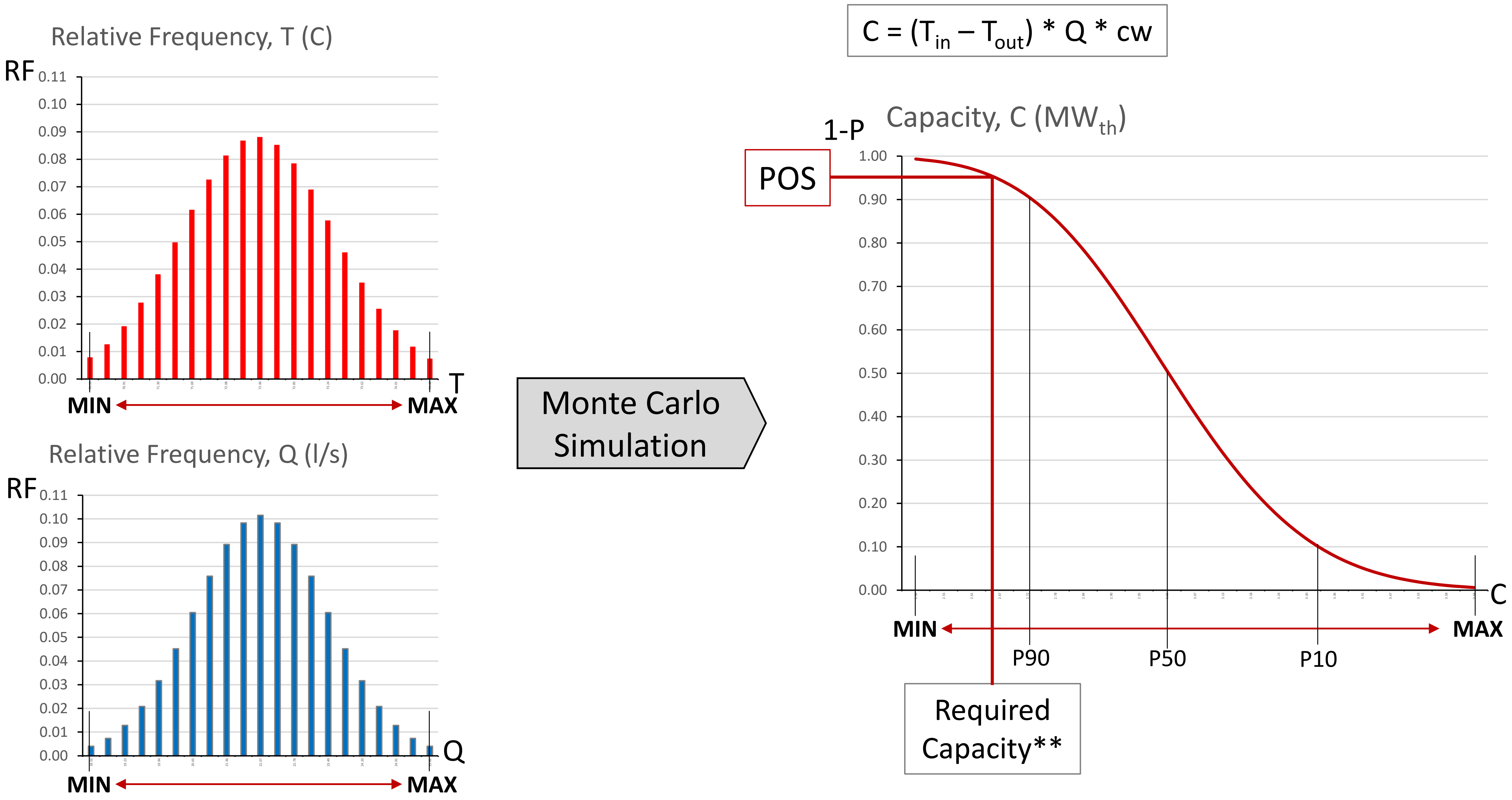
- (Geological) chance for a successful geothermal development
- Probability of sufficient initial geothermal capacity

Similar to hydrocarbon exploration

↓

Similar assessment methodology?

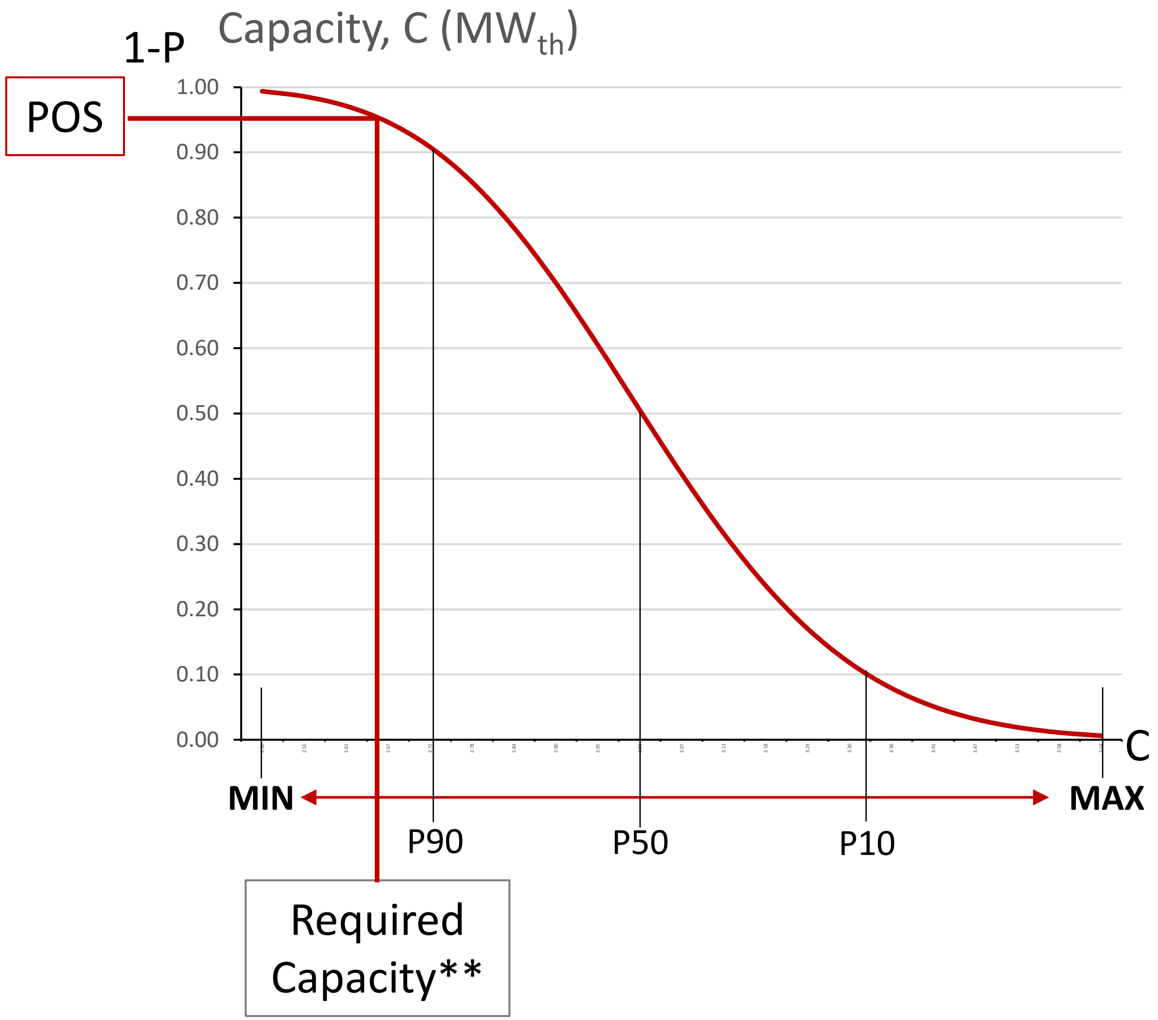
*POS ASSESSMENT IN GEOTHERMAL – EXISTING PRACTICE**



**The Netherlands Organization for Applied Scientific Research (TNO)*

*** Insured against geological failure*

POS ASSESSMENT IN GEOTHERMAL – EXISTING PRACTICE*



Concerns:

- What if aquifer is not present? Even if geological interpretation suggest…?
- What if the aquifer will produce dry well-test? Even if most (but not all) of the wells drilled to the same aquifer produced water…?
- What if the geochemistry of the water will be as unfavorable as it hinders fluid production?
- What if temperature will be as low as it makes energy production uneconomic? Even if flow rate is favorable…?

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POS ASSESSMENT IN GEOTHERMAL – INTRODUCING the PRACTICE of O&G

Combined convection/conduction play; Well-multiplets; District heating

Ingredients :

- Development of aquifer formation
- Sufficient initial flow-rate
- Favorable water geochemistry
- Sufficient aquifer temperature

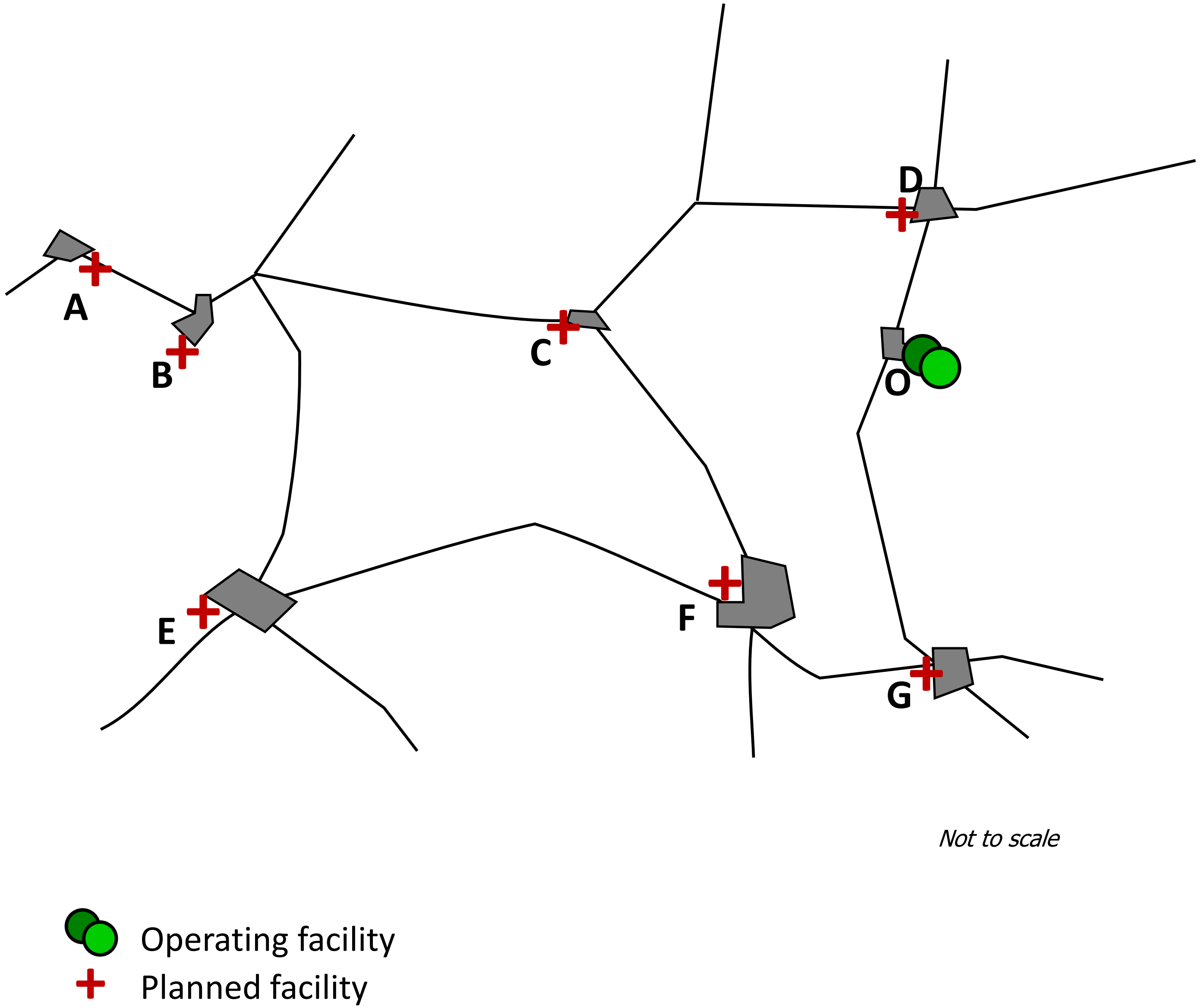
POS Components

- **Aquifer Presence**
- **Aquifer Quality**
- **Fluid Quality**
- **Temperature**

Risking (Risk = 1 – Probability):

1. How much chance (POS) do we have for the Aquifer?
2. If Aquifer is present, how much chance (POS) do we have for sufficient initial flow rates?
3. If Aquifer quality is provided, how much chance (POS) do we have for favorable geochemistry of water which will not hinder initial energy production?
4. How much chance (POS) do we have for aquifer temperature sufficient for district heating?

ENERGY NEED



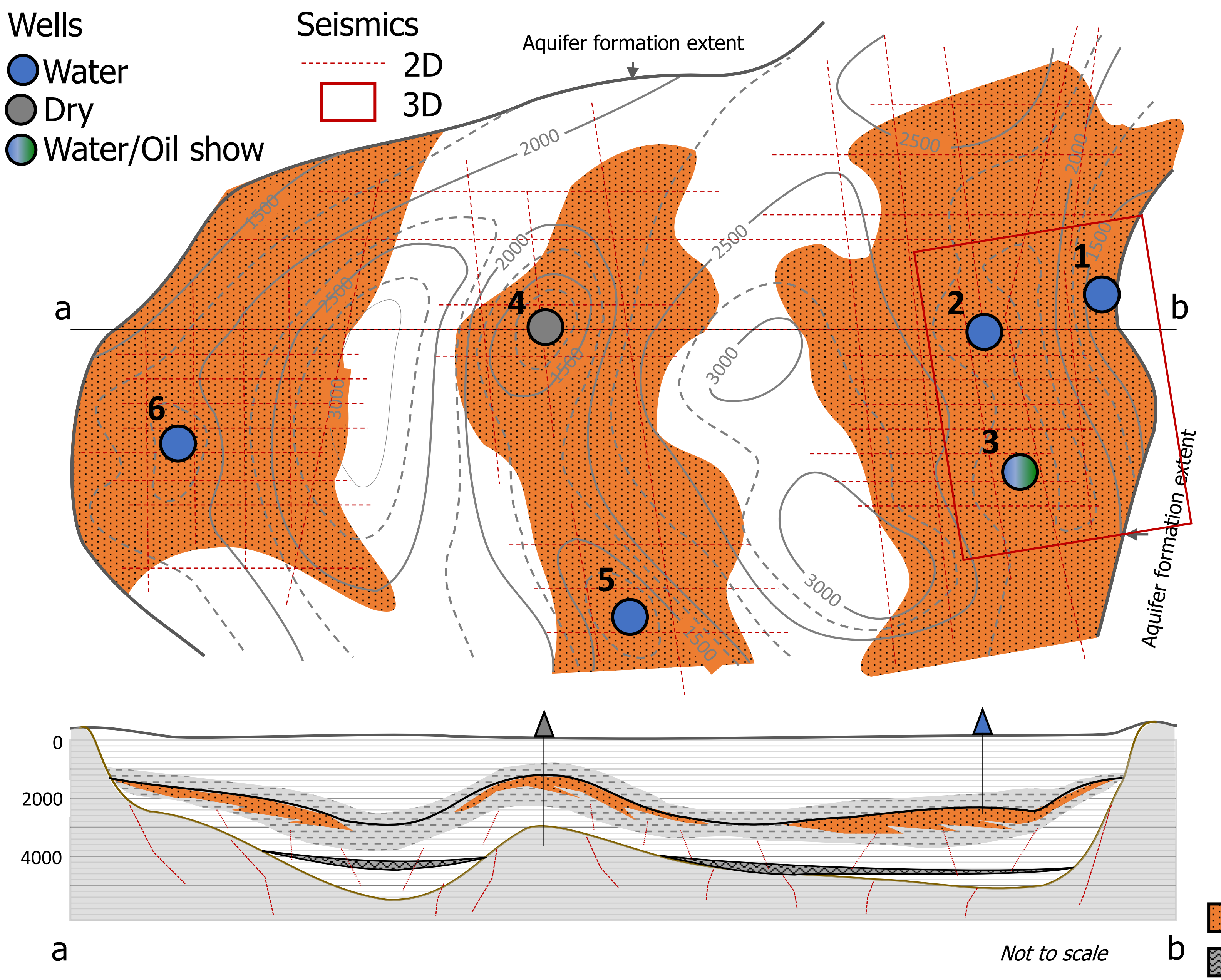
Operating doublet (O)

- Re-purposed unsuccessful hydrocarbon exploration well tested water
- Capacity: 2.5 MW_{th}

Geothermal energy need:

Site	Capacity (MW_{th})
A	2.1
B	2.5
C	4.8
D	6.2
E	8.5
F	10.7
G	6.0

GEOTHERMAL POTENTIAL: AQUIFER



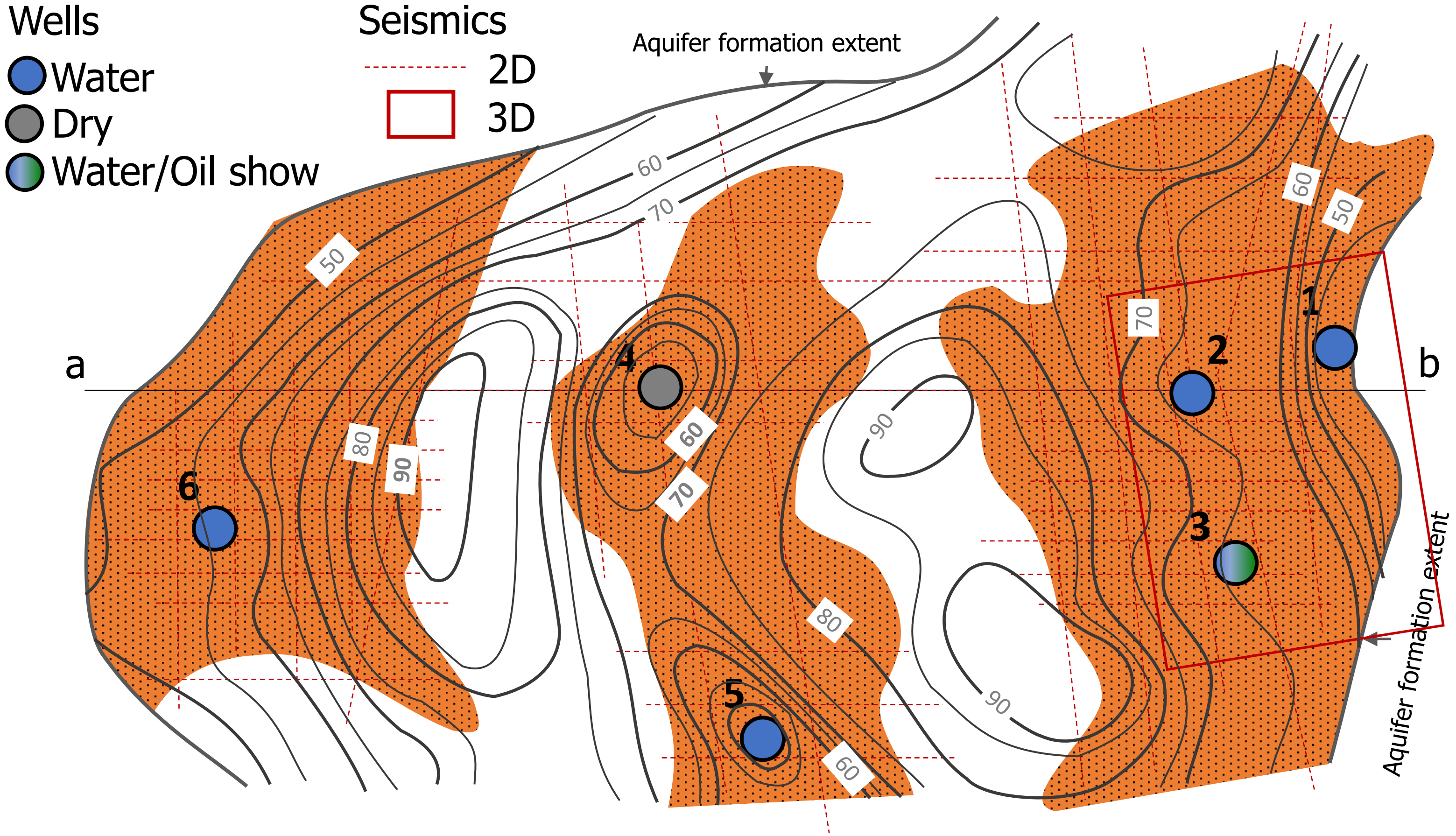
Aquifer: Marine Sandstone

- Mapped by well-tied seismic
- Well-logs, cores available
- Depth: 1,200 – 3,000 m
- Thickness: 0 – 1,000 m
- Porosity: 12-18%
- Permeability: 3-12 mD

Wells:

Nr	Depth (m)	Thickness (m)	Test
1	1,475	185	Water: 18.3 l/s
2	2,030	950	Water: 22.5 l/s
3	2,050	870	Oily water: 25.4 l/s
4	1,205	476	Dry (no inflow)
5	1,210	320	Water: 12.8 l/s
6	1,810	510	Water: 17.3 l/s

GEOTHERMAL POTENTIAL: TEMPERATURE

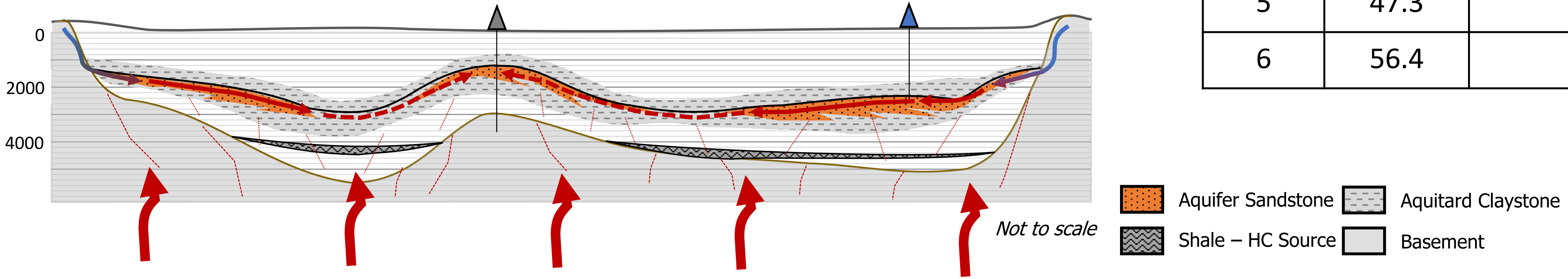


Aquifer temperature

- Defined by heat flow densities & depth
- Modified by regional waterflow
- Ranges between 40 and 90 C
- Geothermal gradient: 30-42 C/km

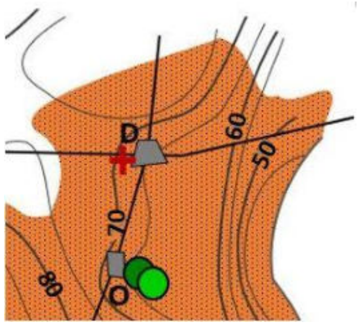
Wells:

Nr	BH T (C)	Gradient (C/km)
1	44.3	30.0
2	62.0	30.5
3	64.2	31.3
4	49.7	41.2
5	47.3	39.1
6	56.4	31.2



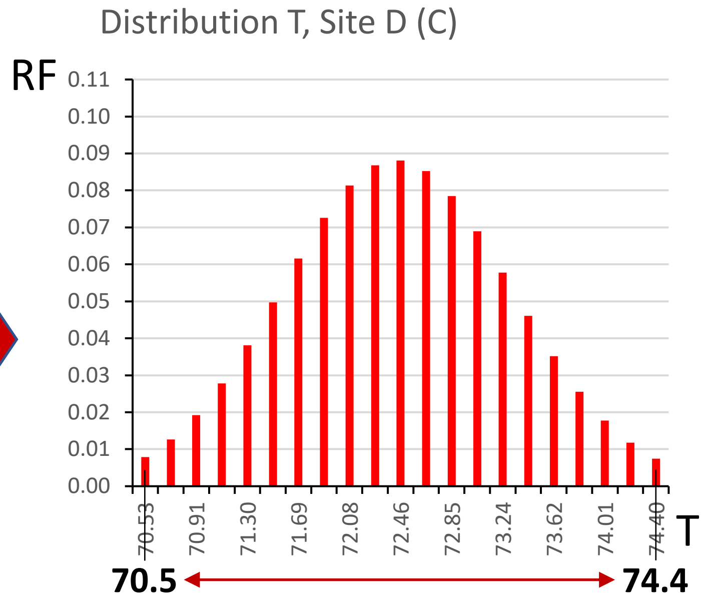
UNRISKED GEOTHERMAL CAPACITY ESTIMATION @ DEVELOPMENT SITES*

Site D



Aquifer T estimation:

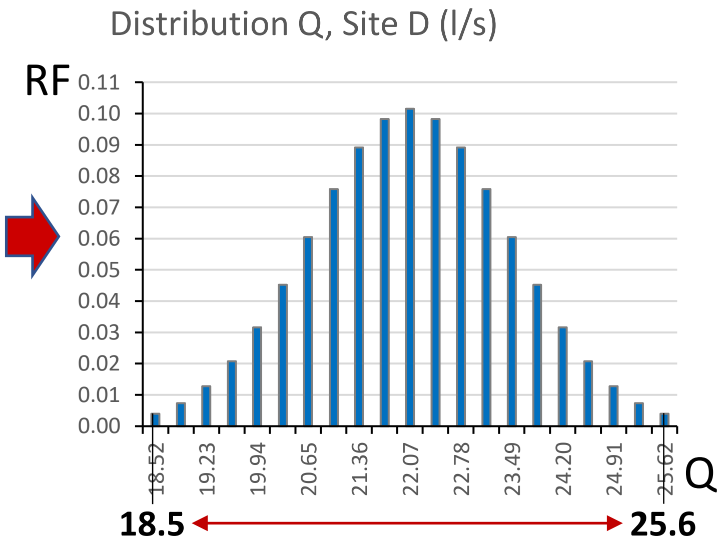
- Aquifer depth
- Geothermal gradient



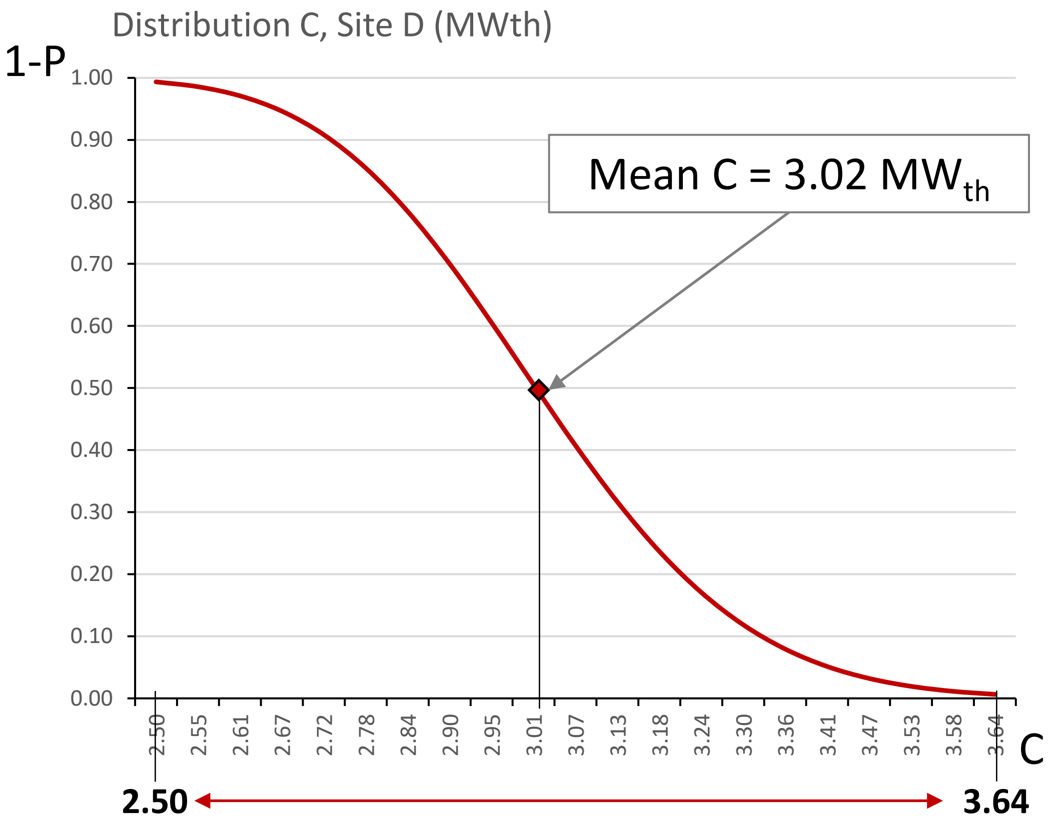
Flow rate estimation:

Measured Q-s at wells:

- Study area
- Database of analogues

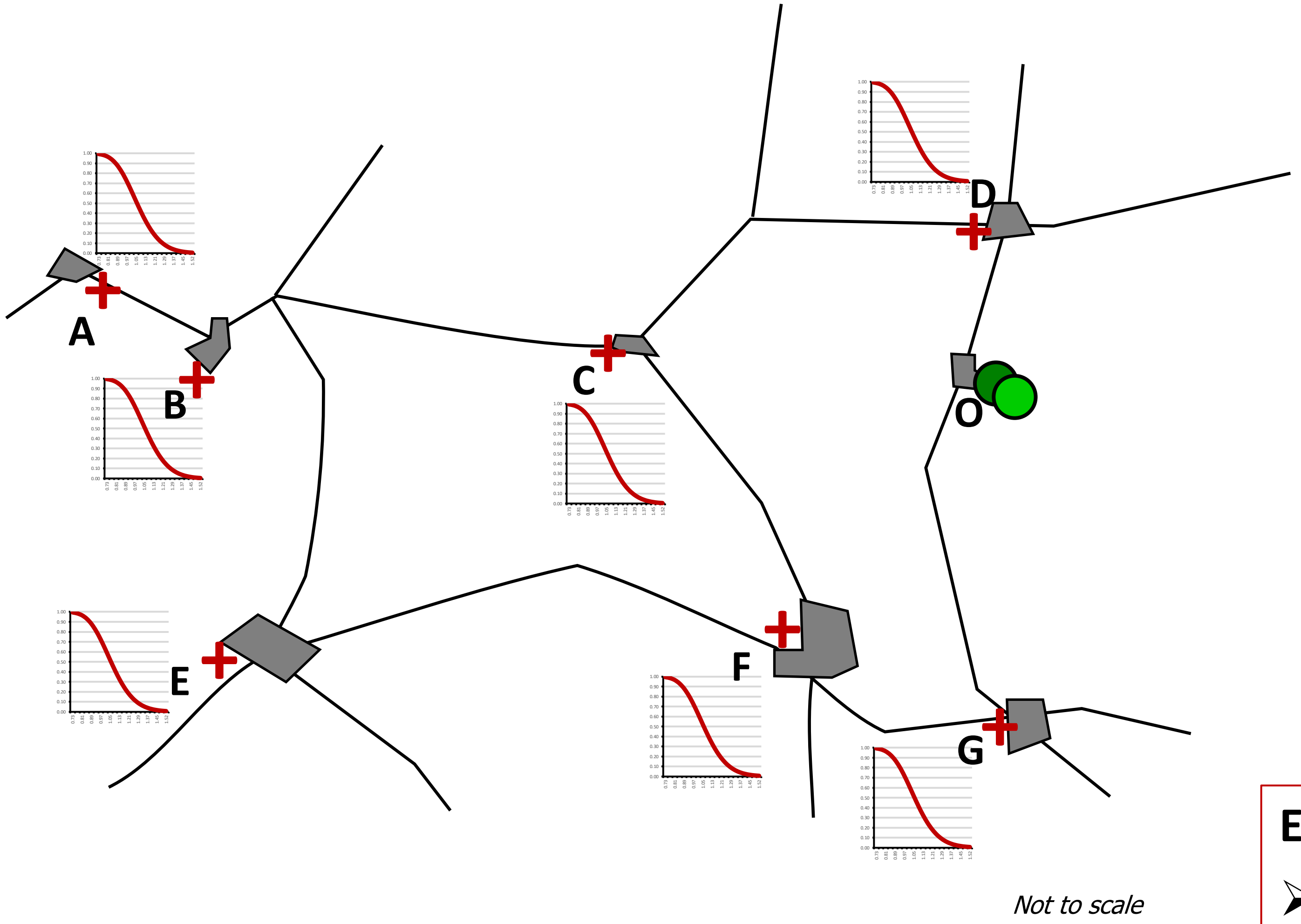


$C = (T_{in} - T_{out}) * Q * cw$



** For 1 doublet*

UNRISKED GEOTHERMAL CAPACITY ESTIMATION @ DEVELOPMENT SITES*



Operating facility

Planned facility

Capacity (MW_{th})

Site	Min	Max	Mean
A	0.73	1.52	**1.11**
B	2.17	3.44	**2.74**
C	1.91	3.16	**2.47**
D	2.50	3.64	**3.02**
E	2.24	3.67	**2.88**
F	2.59	4.74	**3.52**
G	2.51	3.81	**3.10**
O			**2.50**

!

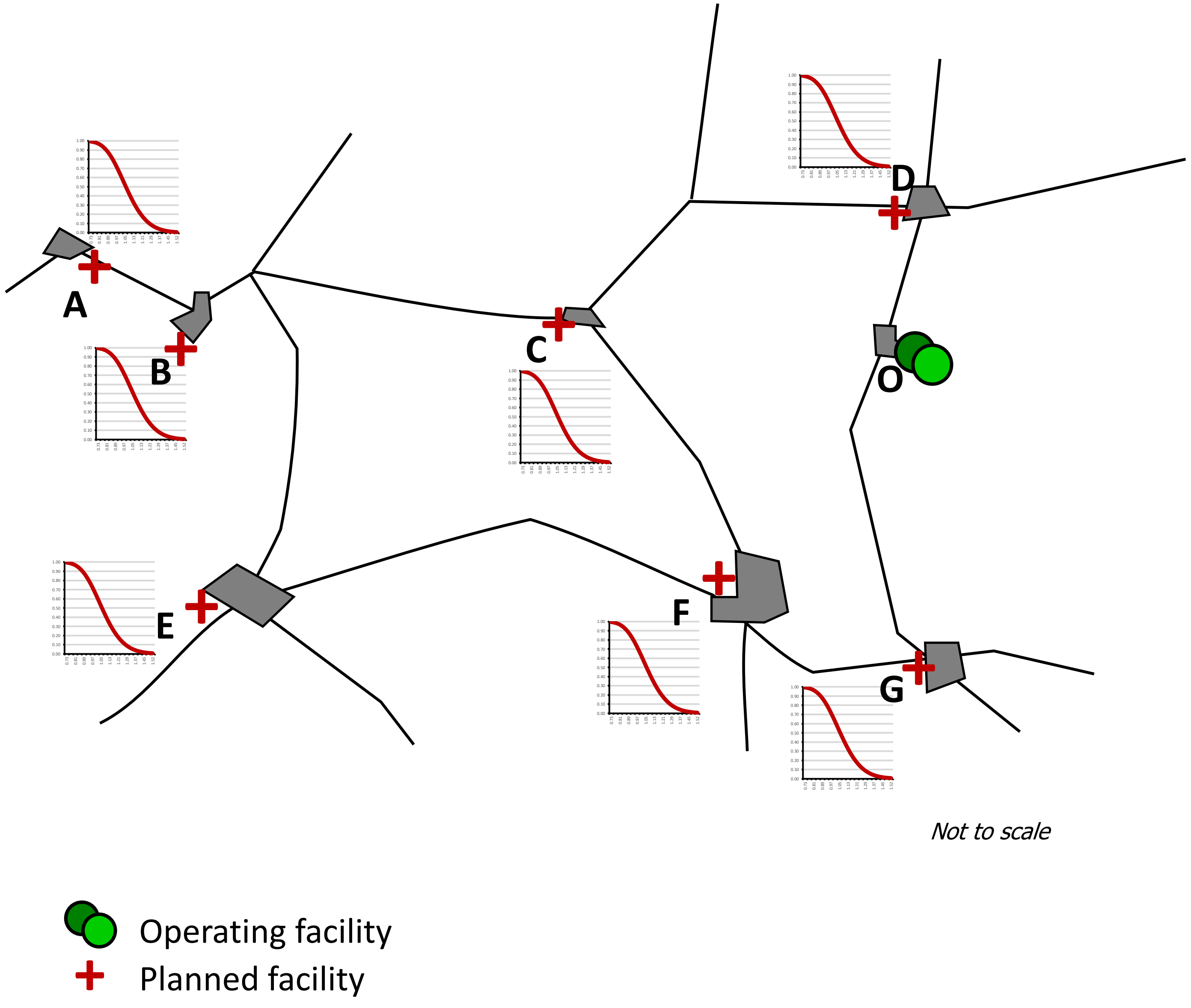
Economic capacity threshold:

- 1.25 MW_{th} / production well to provide positive operating cash-flow;

  (Revenue – O&M Costs)/Well > 0

** For 1 doublet*

UNRISKED GEOTHERMAL CAPACITIES vs ENERGY NEEDS

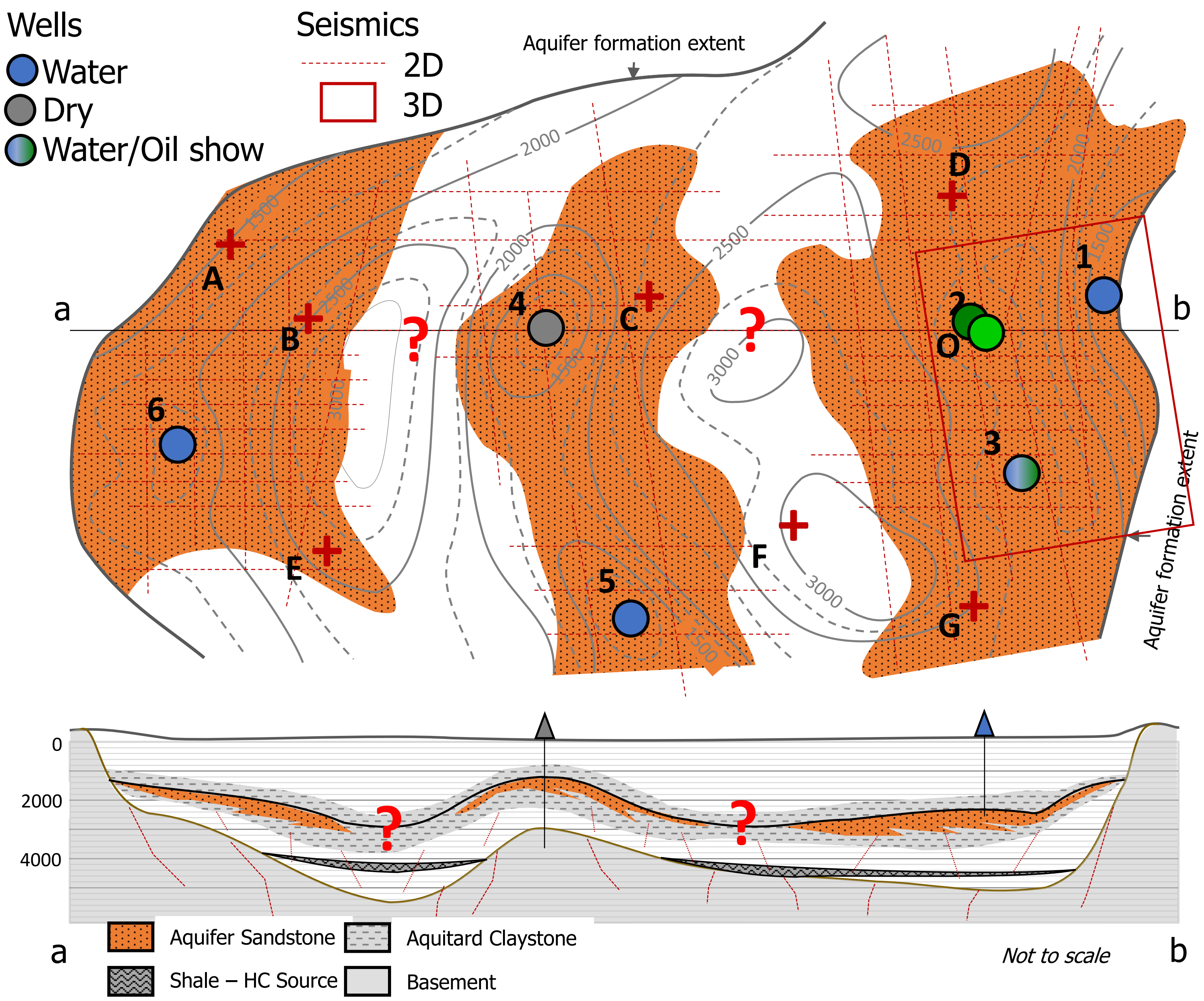


Site	Mean Capacity / Prod. Well (MW_{th})	Required Capacity (MW_{th})	Nr. Required Wells
A	1.11	2.1	2
B	2.74	2.5	1
C	2.47	4.8	2
D	3.02	6.2	2
E	2.88	8.5	3
F	3.52	10.7	3
G	3.10	6.0	2

How much (geological) chance do we have to meet the required capacities?

Probability of Success (POS)?

RISK ASSESSMENT: AQUIFER PRESENCE



Aquifer Sandstone Development

Confidence by:

- ➢ Supportiveness of data

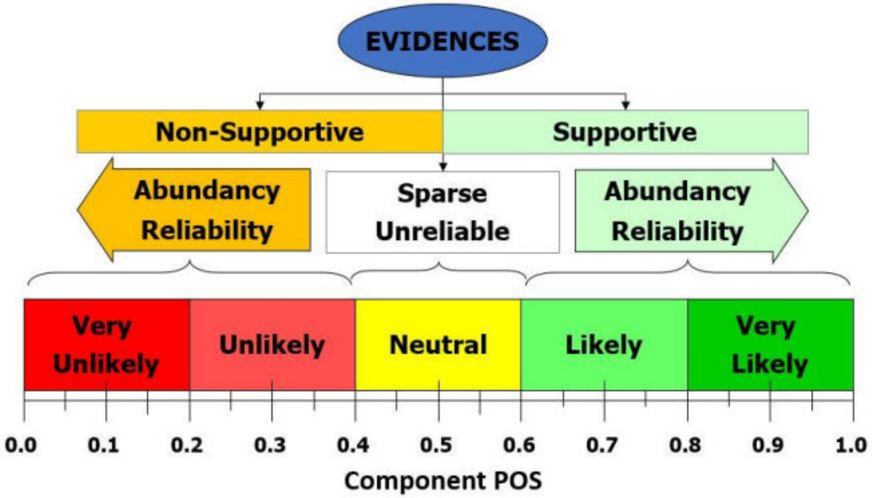
To what extent seismic interpretation confirm/disaffirm sandstone presence?

- ➢ Exploration maturity

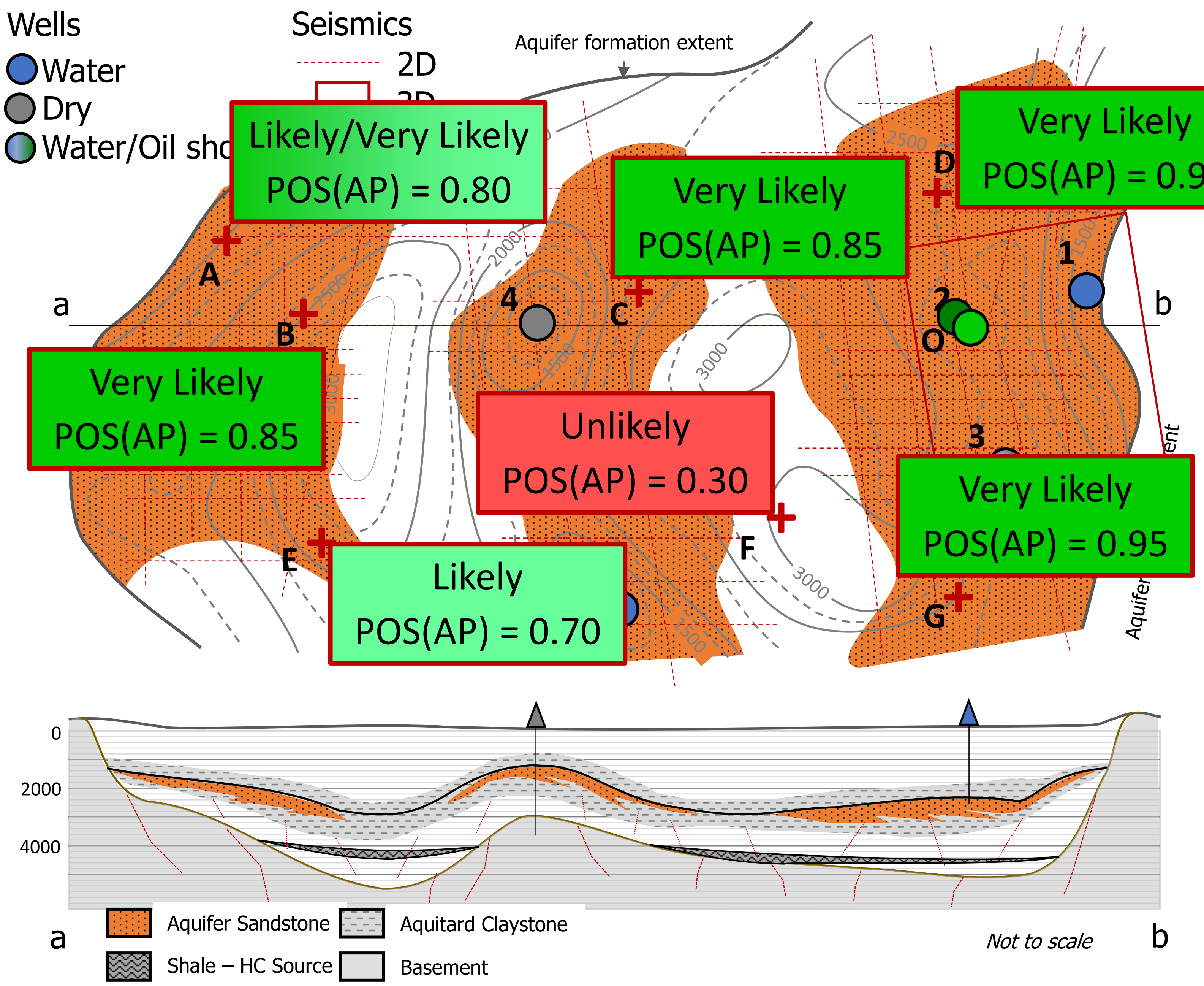
High: Well-tied 2D & 3D

Low: Well-tied 2D

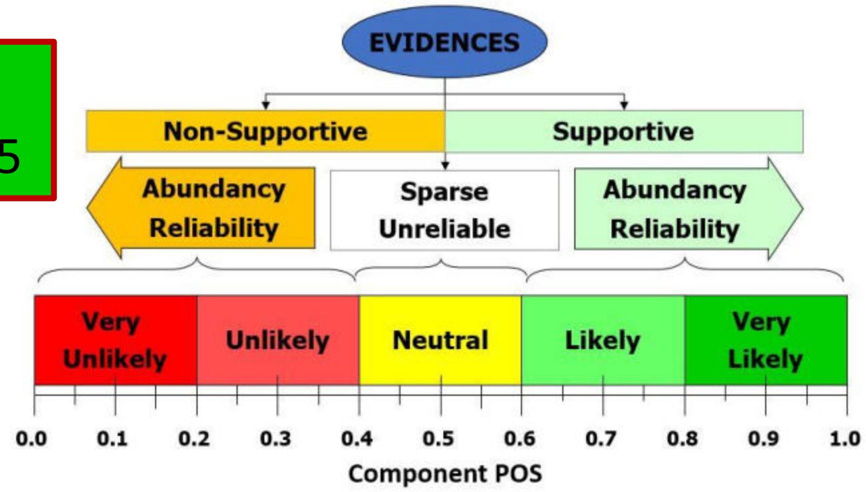
Sparse: Poor or no seismic coverage



RISK ASSESSMENT: AQUIFER PRESENCE



Aquifer Presence



Evidence's supportiveness

A, B, C, D, G: Strong supportive

E: Weak supportive

F: Non-supportive

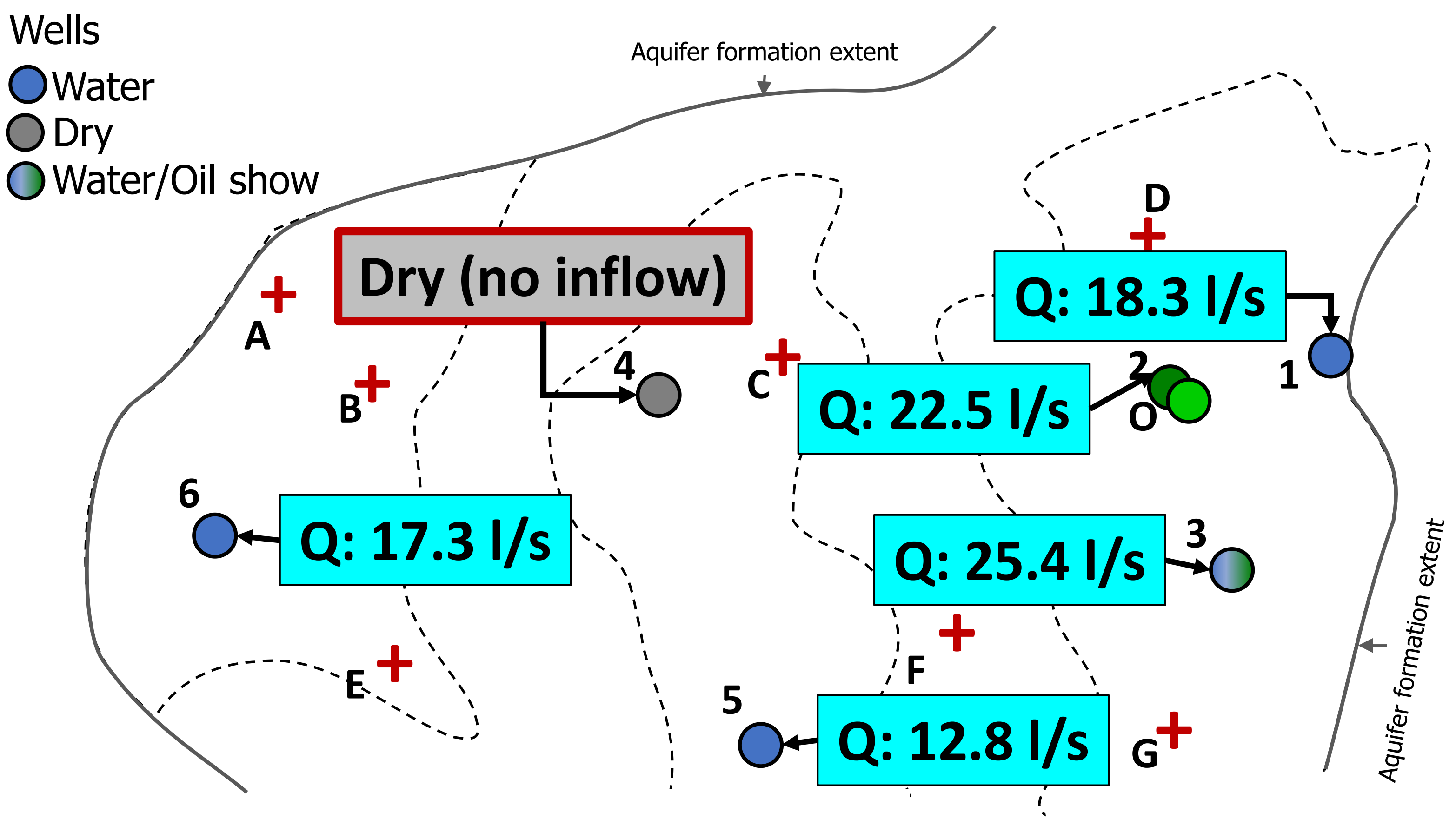
Exploration maturity

D, G: High

A, B, E, C: Low

F: Sparse

RISK ASSESSMENT: AQUIFER QUALITY



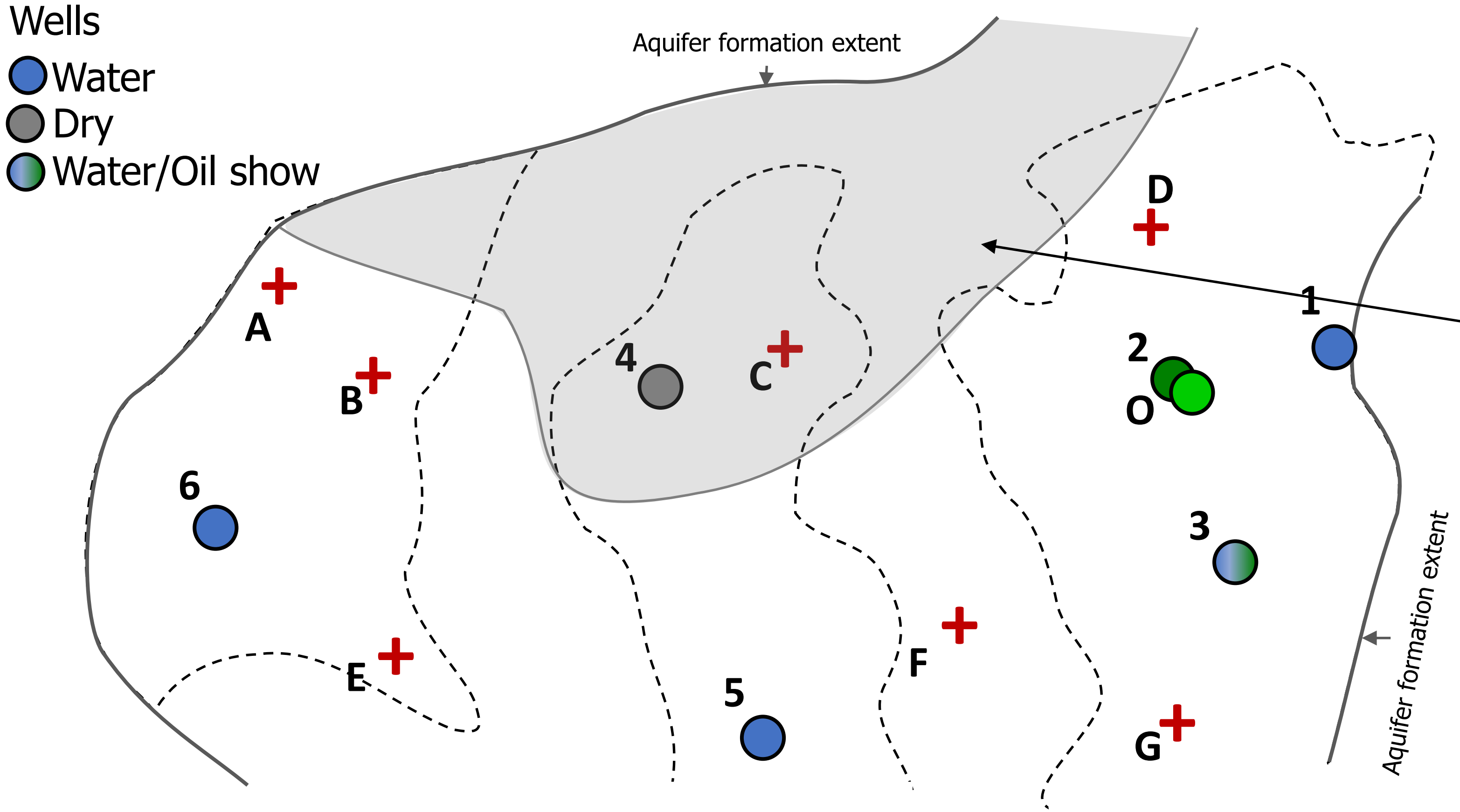
Aquifer Quality

Risk: Even if aquifer present, the well is dry (no fluid inflow) – W4

Risk factor: Tight sandstone

How much POS do we have for deliverability (sufficient water inflow) at development sites?

RISK ASSESSMENT: AQUIFER QUALITY



Aquifer Quality

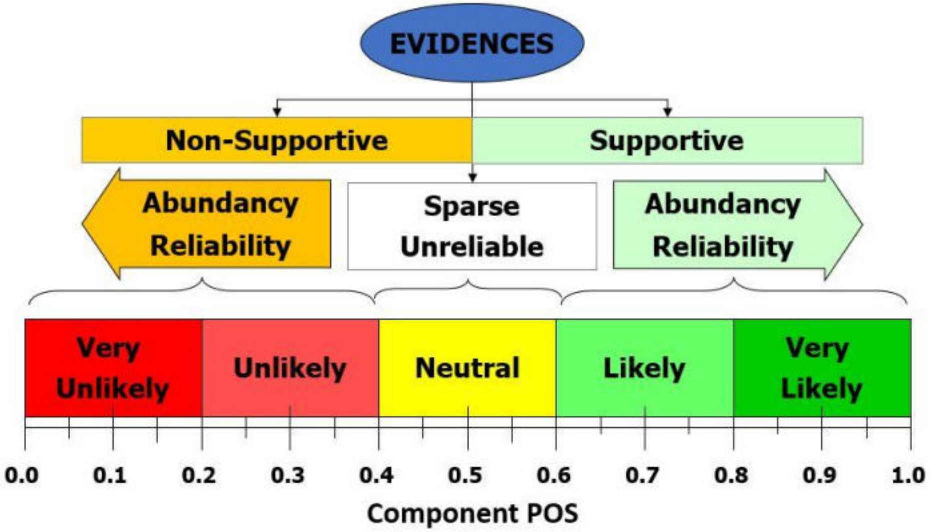
Confidence by:

- Supportiveness of data

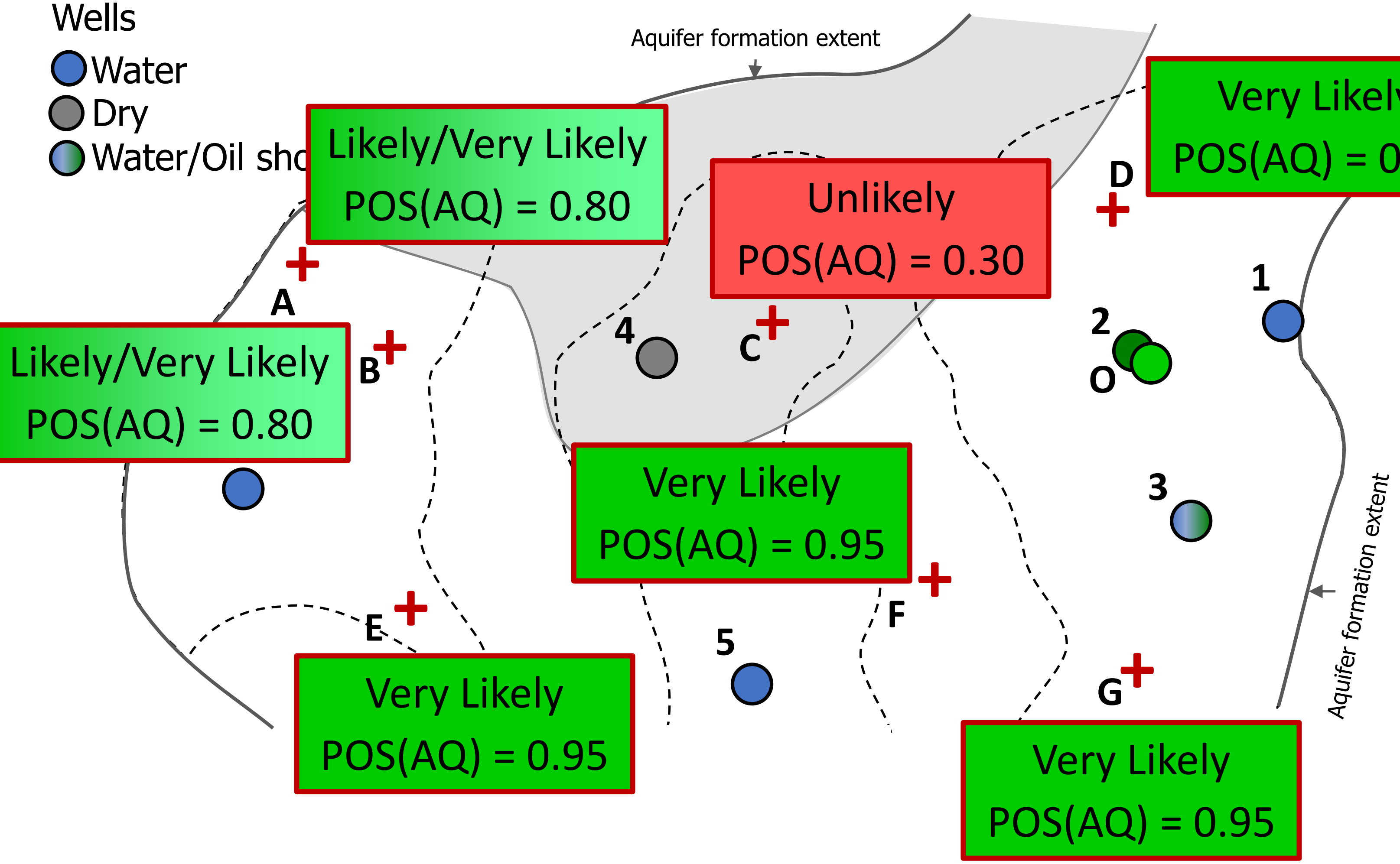
Sedimentary environment study suggests that tight sandstones may occur with higher probability northward

- Exploration maturity

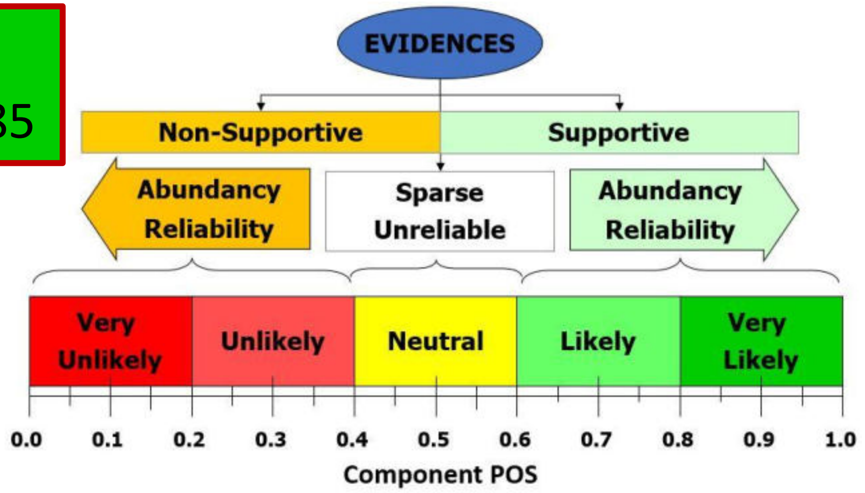
Defined by distance of development sites from wells



RISK ASSESSMENT: AQUIFER QUALITY



Aquifer Quality



Evidence's supportiveness

E, F, G: Strong supportive

A, B, D: Weak supportive

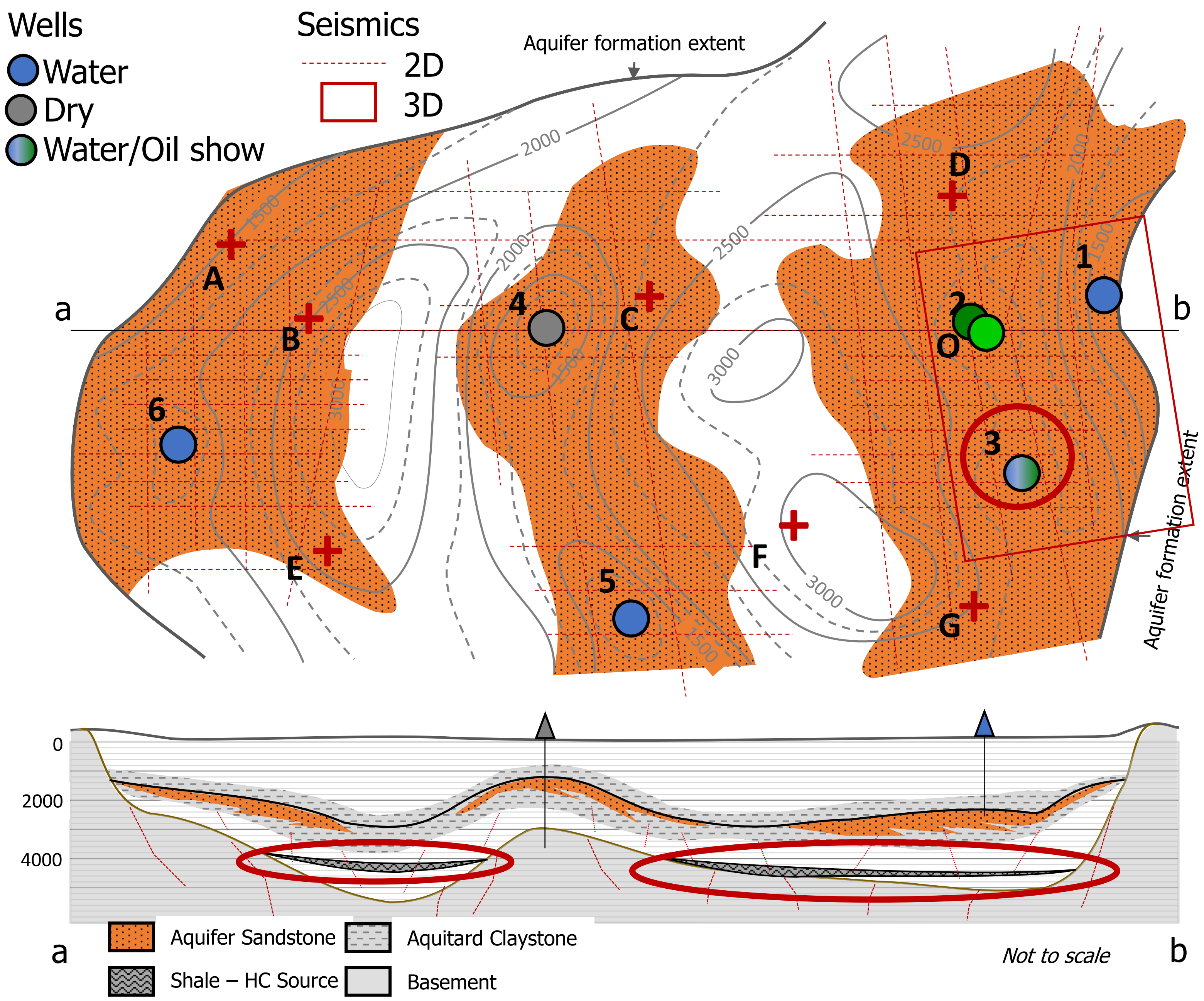
C: Non-supportive

Exploration maturity

C, D: High

A, B, E, F, G: Low

RISK ASSESSMENT: FLUID'S QUALITY



Fluid Quality

Risk: Geochemistry of the water is so adverse that it hinders production

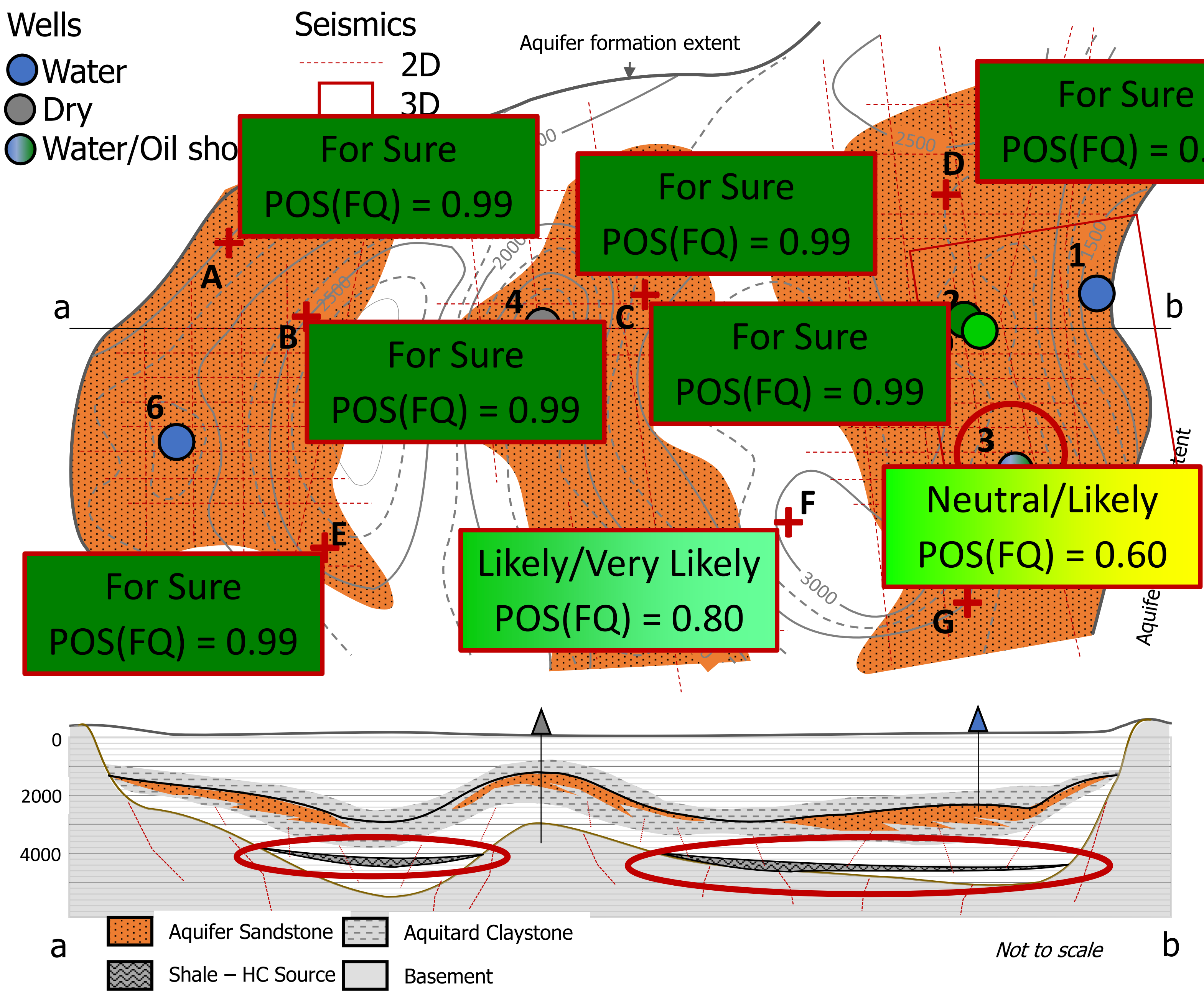
Risk factor: Oil content – as in W3

Source rock & migration pathways confirmed by seismic interpretation

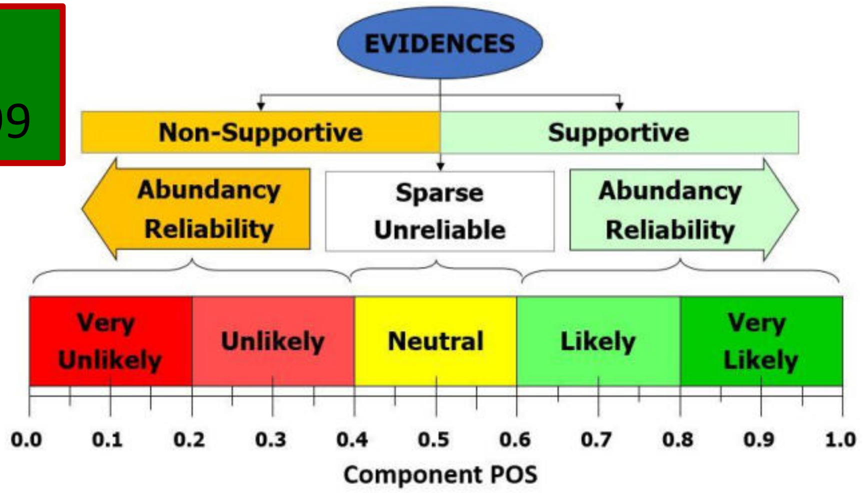
How much POS do we have for oil-free thermal water at development sites?

How much risk (1-POS) do we have to find a „hidden" HC-accumulation on the migration pathway?

RISK ASSESSMENT: FLUID'S QUALITY



Fluid Quality



Evidence's supportiveness

A, B, C, D, E: Strong supportive

F: Weak supportive

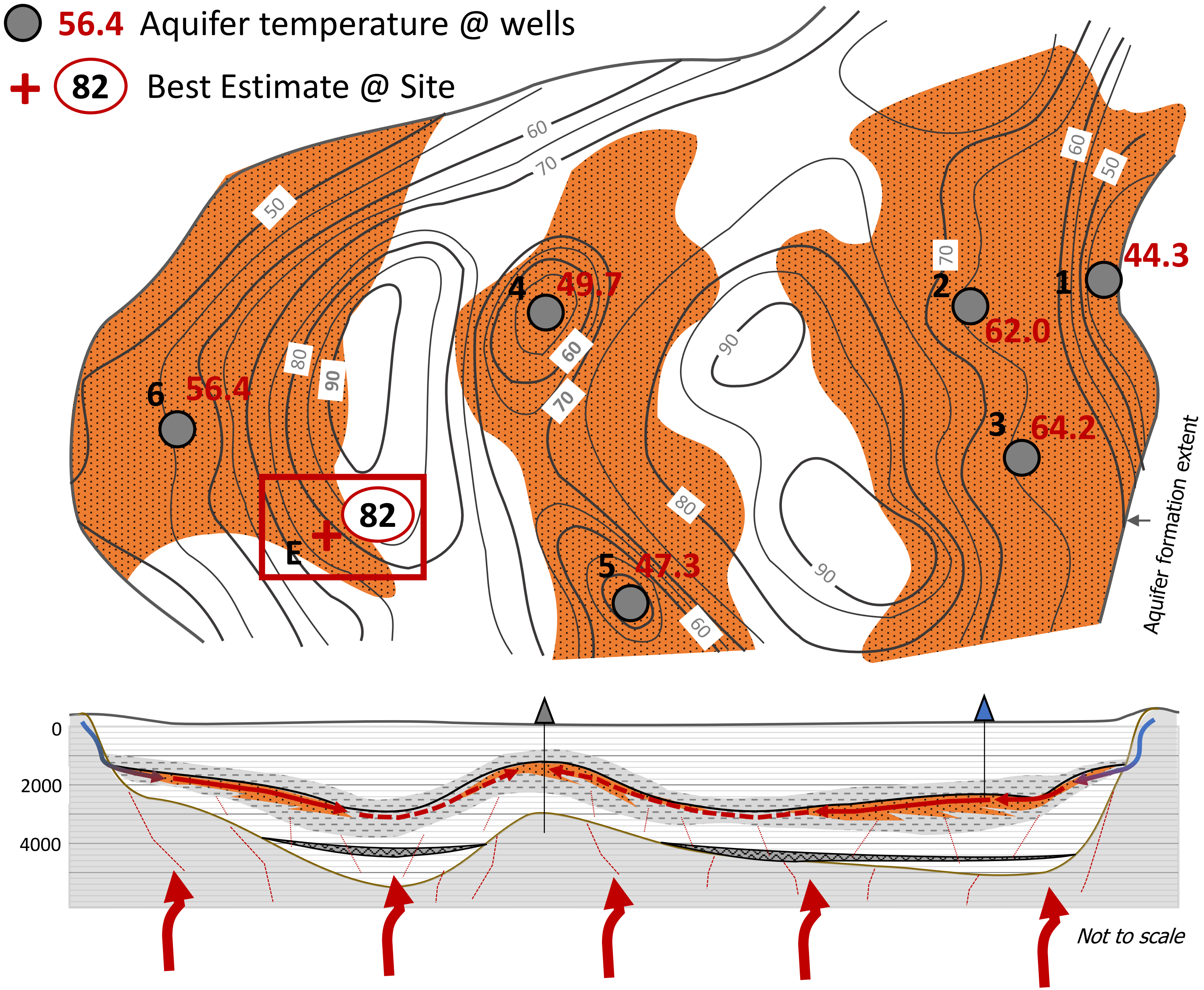
G: Neutral

Exploration maturity

A, B, C, D, E, G: High

F: Sparse

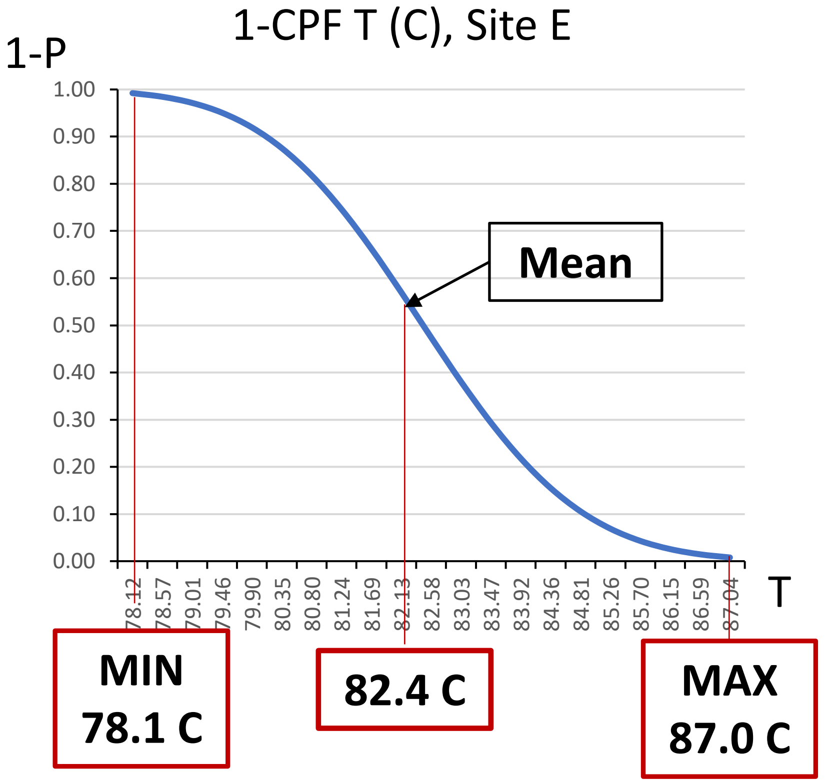
RISK ASSESSMENT: TEMPERATURE



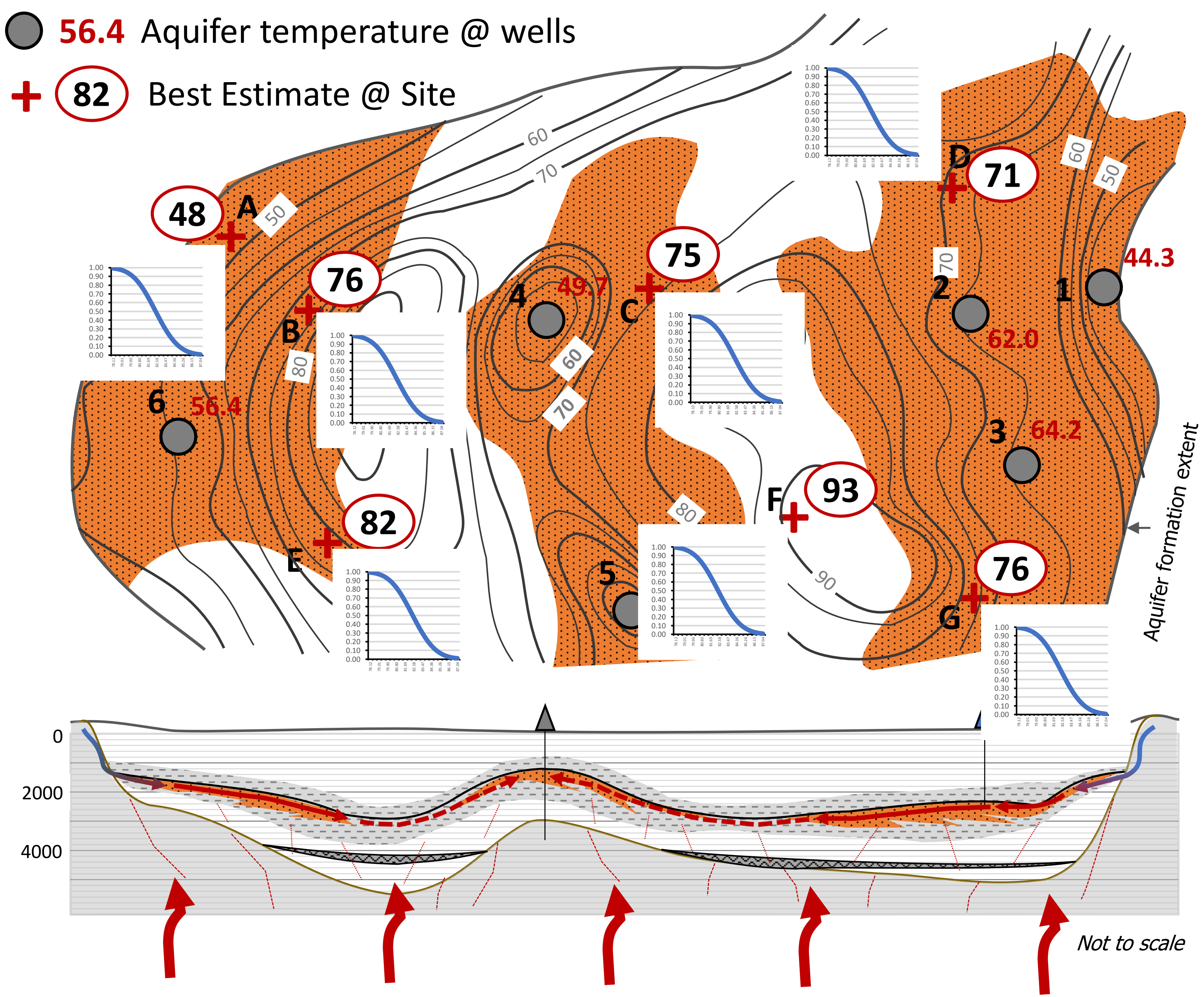
Temperature map:

- Depth to top aquifer
- Geothermal gradient

Estimations are characterized by uncertainty



RISK ASSESSMENT: TEMPERATURE



Temperature ranges at development sites:

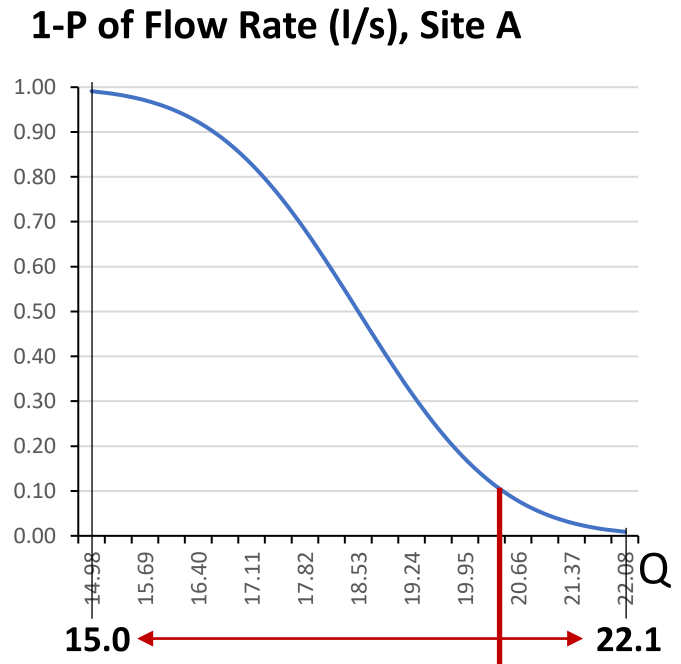
Site	MIN (P99)	MAX (P01)	Mean
A	46.4	51.7	48.9
B	76.0	81.6	78.7
C	75.3	81.0	78.0
D	70.5	74.4	72.3
E	78.1	87.0	82.4
F	86.4	108.9	97.0
G	76.0	81.6	78.7

How much POS do we have for the sufficient aquifer T?

RISK ASSESSMENT: TEMPERATURE

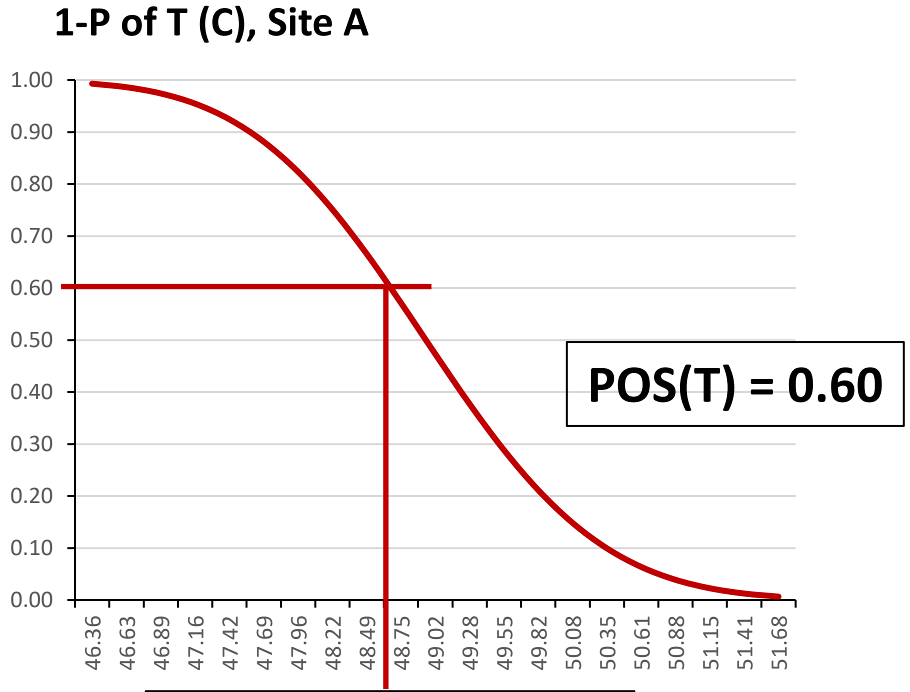
Considerations:

- POS of T: The probability of the „threshold” temperature
- If estimated T is below the „threshold”, the minimum capacity (in study case 1.5 MW_{th}) were not met – Even if flow-rate (Q) is the High Estimate (P10)
- Q estimation: Based on flow rates of neighboring wells; Uncertainty added



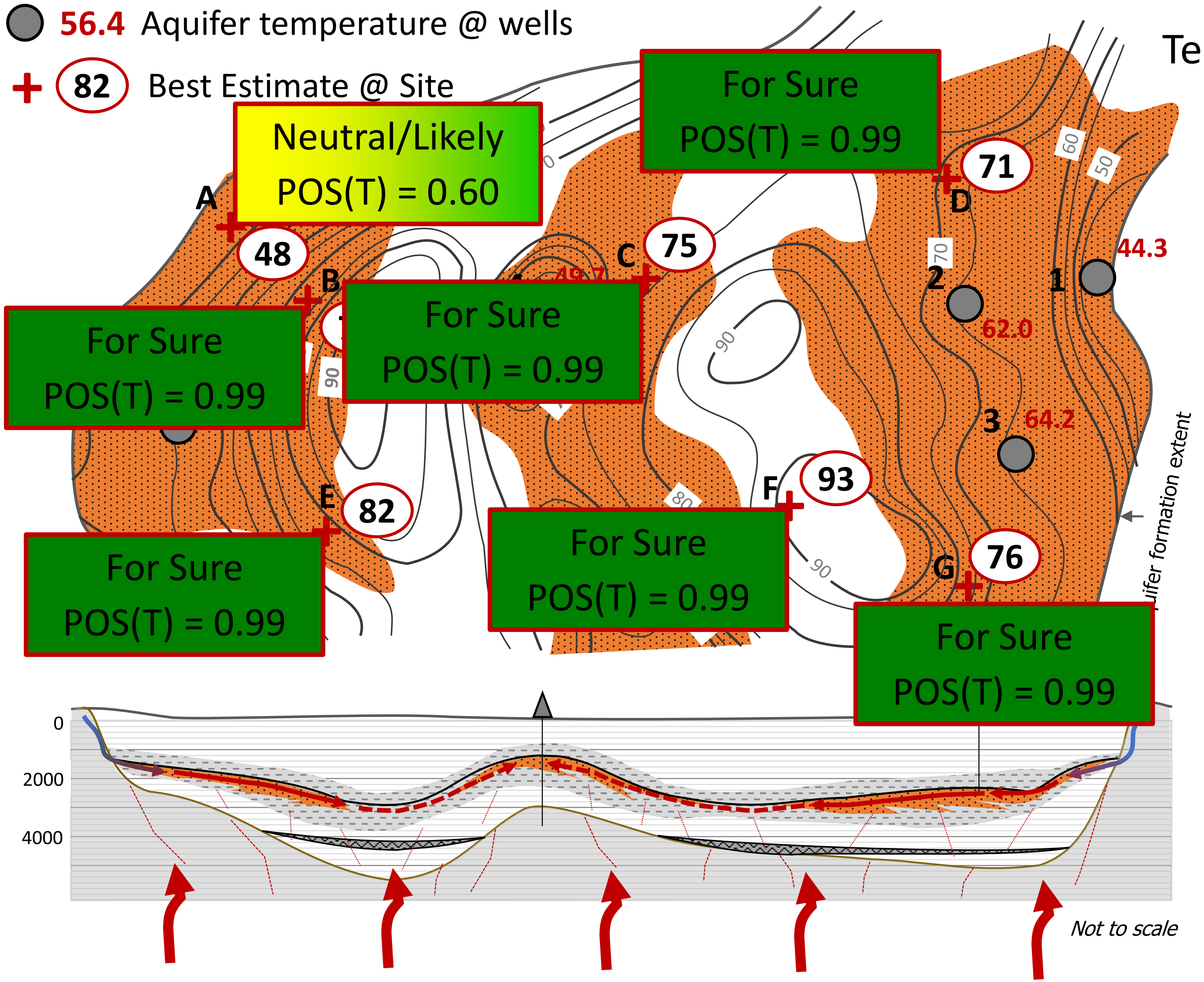
High Estimate (P10) Q 20.4 l/s

To have 1.5 MW_{th} capacity at 20.4 l/s flow rate **48.6 C** aquifer temperature is needed



Threshold T = 48.6 C

RISK ASSESSMENT: TEMPERATURE



Temperature POS @ Development Sites

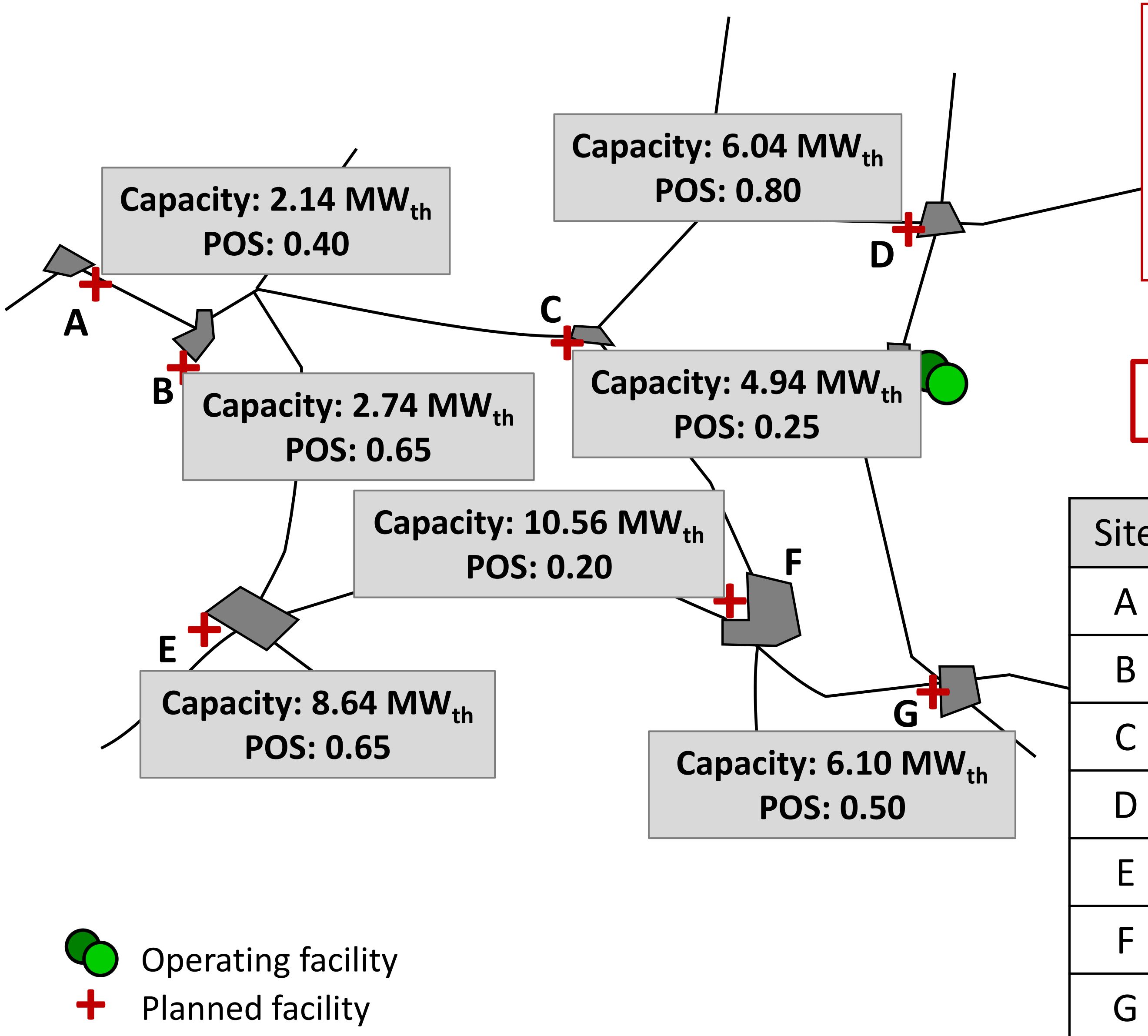
Site	MIN T	Threshold T	POS(T)
A	46.4	48.6	0.60
B	76.0	48.5	0.99
C	75.3	50.1	0.99
D	70.5	46.3	0.99
E	78.1	48.7	0.99
F	86.4	48.1	0.99
G	76.0	47.0	0.99

Sites B, C, D, E, F, G:

MIN T > Threshold T

POS(T) = 1

GEOTHERMAL POS QUANTIFICATION



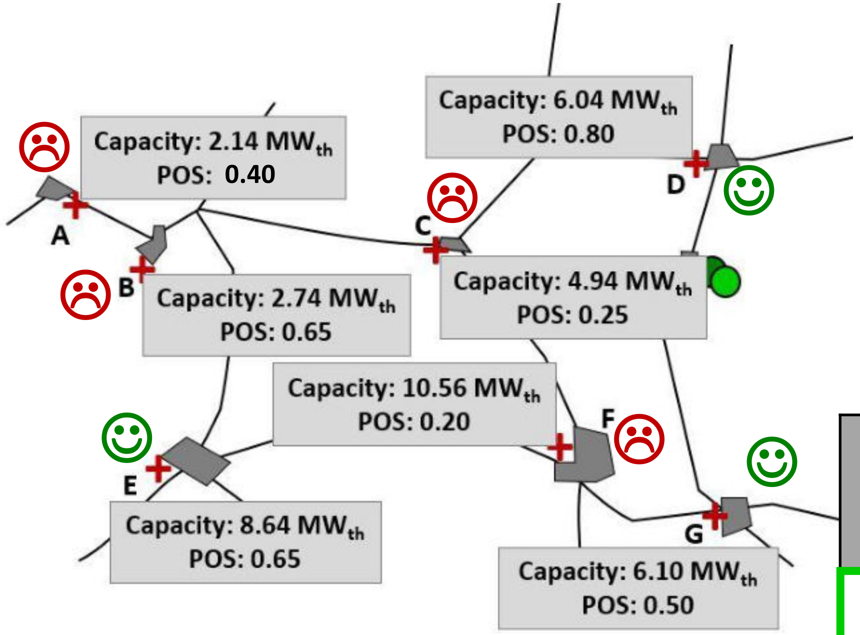
Aquifer Presence
Aquifer Quality
Fluid Quality
Temperature

→ Independent or conditional risk factors

POS = POS(AP) x POS(AQ) x POS(FQ) x POS(T)

Site	POS(AP)	POS(AQ)	POS(FQ)	POS(T)	**POS**	**Risk**
A	0.80	0.80	0.99	0.60	**0.40**	**60%**
B	0.85	0.80	0.99	0.99	**0.65**	**35%**
C	0.85	0.30	0.99	0.99	**0.25**	**75%**
D	0.95	0.85	0.99	0.99	**0.80**	**20%**
E	0.70	0.95	0.99	0.99	**0.65**	**35%**
F	0.30	0.95	0.60	0.99	**0.20**	**80%**
G	0.90	0.95	0.60	0.99	**0.50**	**50%**
O	1.00	1.00	1.00	1.00	**1.00**	-

GEOTHERMAL POS IN FUND MANAGEMENT



GeoTherm Fund (12 mn €) for district heating greenification

- ➢ Projects apply for grants
- ➢ Total grant need: 24.8 mn €…
- ➢ POS x C could be one of the ranking criteria

Site	POS	C (MW_{th})	POS*C	Grant Need (mn €)	Cum Grant (mn €)
E	0.65	8.64	5.62	5.4	5.4
D	0.80	6.04	4.83	3.0	8.4
G	0.50	6.10	3.05	3.4	11.8
F	0.20	10.56	2.11	6.2	17.9
B	0.65	2.74	1.78	1.7	19.6
C	0.25	4.94	1.24	3.1	22.8
A	0.40	2.14	0.86	2.1	24.8

Granted (E, D, G)

12.0 mn €

Not granted (F, B, C, A)

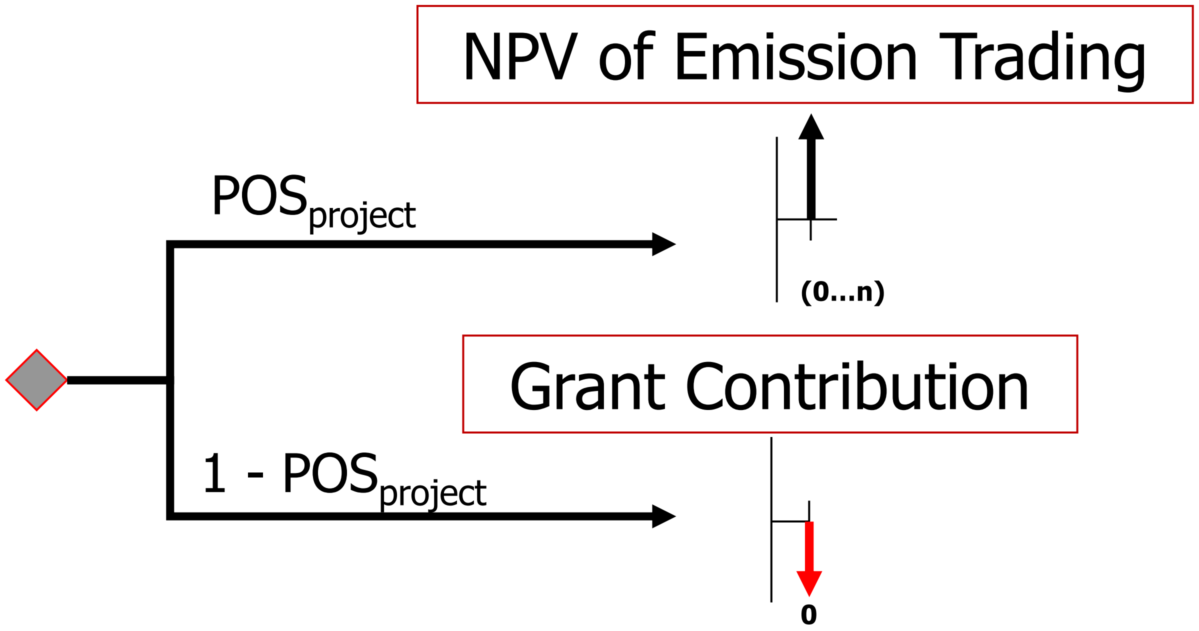
GEOTHERMAL POS & PROJECT ECONOMICS

Fund Management's perspective:

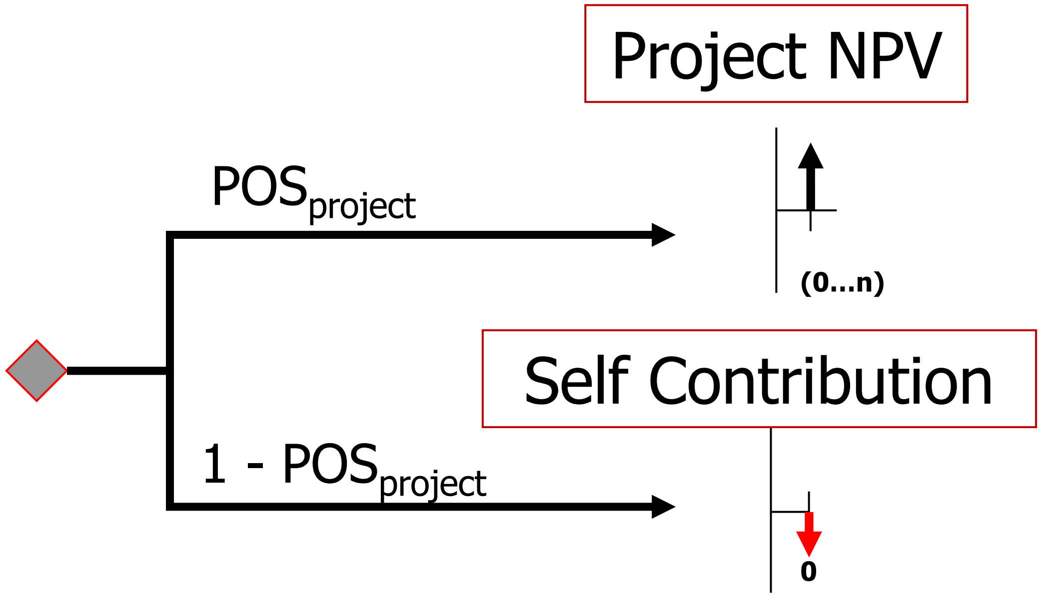
- Use of geothermal energy instead of gas decreases CO_2 emission
- CO_2 is traded – Monetary value – NPV
- Investment is the grant contribution

Developer's perspective:

- Energy production delivers NPV
- Investment is the self contribution

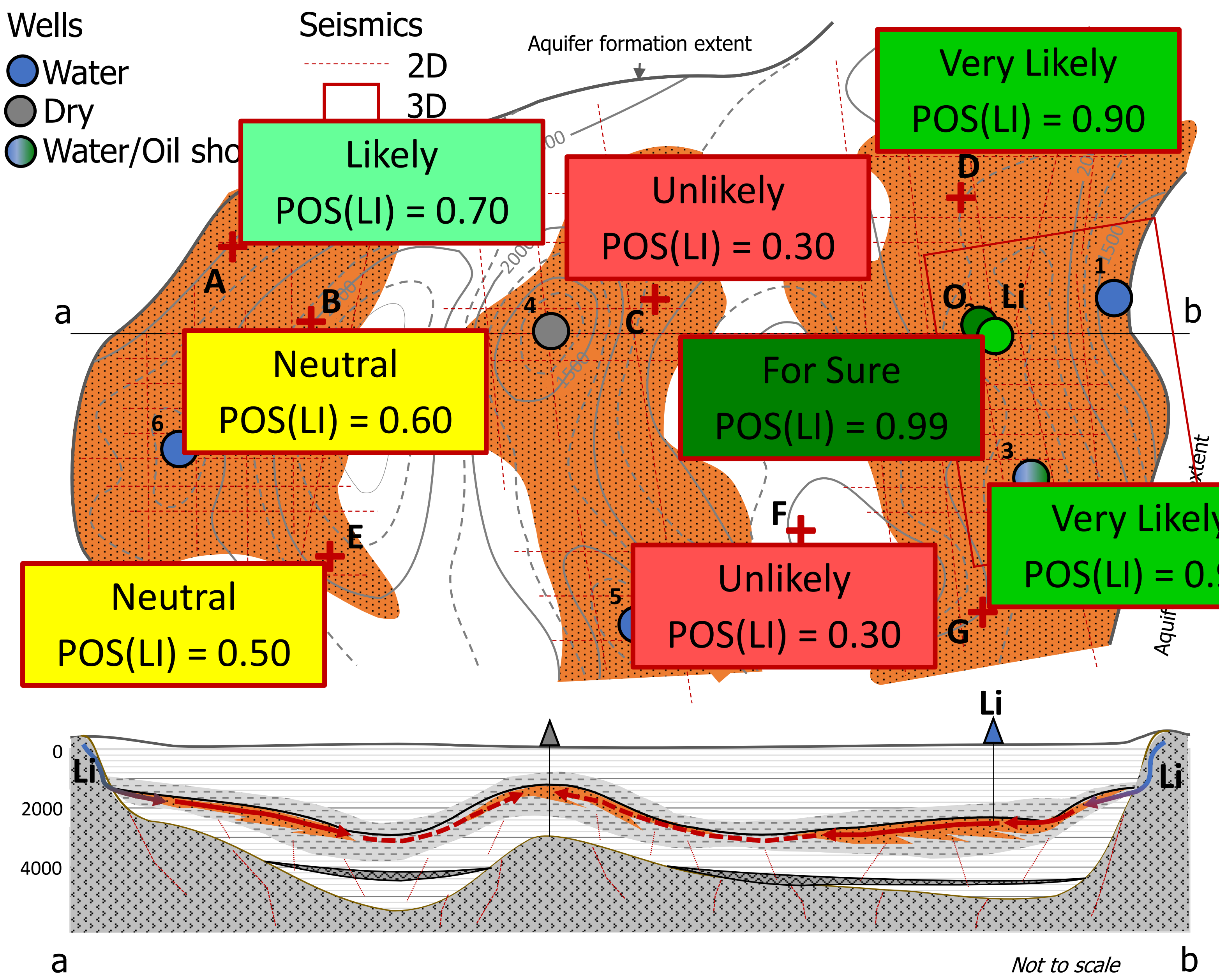


$$ENPV = POS \times NPV - (1 - POS) \times GC$$



$$ENPV = POS \times NPV - (1 - POS) \times SC$$

BONUS: POS OF LITHIUM PRODUCTION



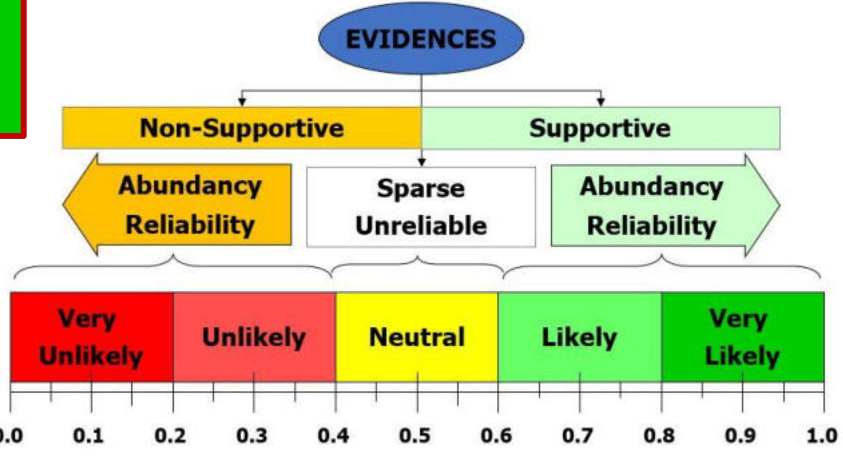
Let's suppose:

Granite basement is source of Lithium

Sandstone aquifer is 2,000 meters deeper…

Significant Li-concentration is observed in the geothermal producing well (O)

POS(LI) assessment

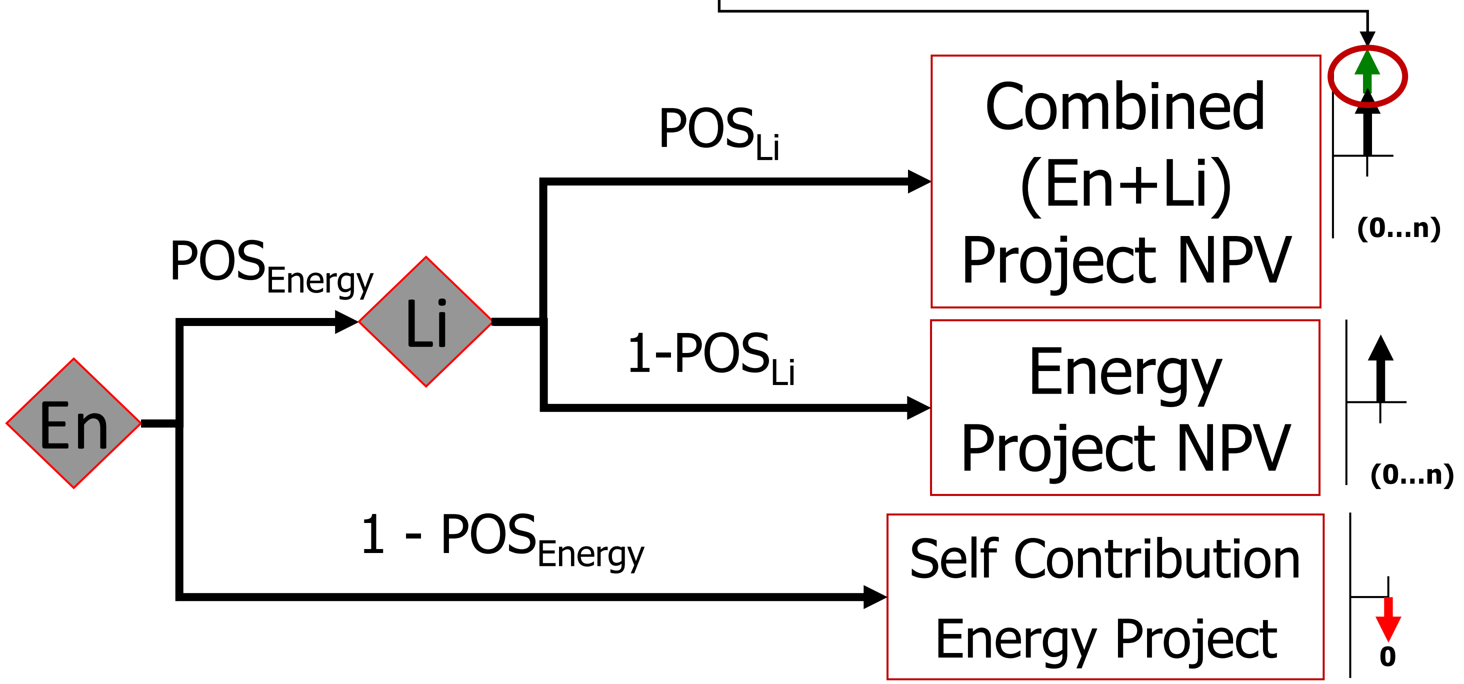


POS of producible Li

GEOTHERMAL POS & PROJECT ECONOMICS – LITHIUM PRODUCTION ADDED

Economics is viewed from the Developer's perspective:

- Sufficient Li-concentration is characterized by POS(LI)
- Li-extraction requires additional investments – added to the energy project's self contribution
- Investment decision is made after the completion of the multiplets
- Li-extraction may bring additional NPV – If Present Value > Discounted Investment (Li)



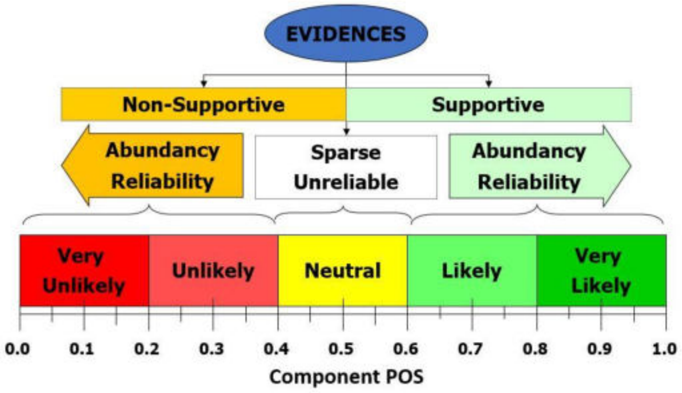
$$ENPV = POS(EN) \times (POS(LI) \times NPV(EN;LI)) + POS(EN) \times [1 - POS(LI)] \times NPV(EN) - [1 - POS(EN)] \times SC(EN)$$

GEOLOGICAL RISK ASSESSMENT IN GEOTHERMAL – SUMMARY

Geothermal POS is the probability of sufficient initial capacity

POS quantification methodology (Similar to hydrocarbon exploration):

- Identification of independent or conditional probability components, e.g.:
  - Aquifer Presence
  - Aquifer Quality
  - Fluid Quality
  - Temperature



- Consideration of data supportiveness and the exploration maturity

Relevance of risk (1 – POS) quantification:

- Ranking of development opportunities ➡ Grant distribution
- Project economics ➡ Fund management's perspective
  ➡ Developer's perspective

Professional Development Workshop on
Critical Raw Materials Content in Thermal Waters:
Analysis and Assessment

Geological risk assessment in geothermal developments: how and why?

Thank you for your attention!

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CA questions: