Headquarters U.S. Air Force

Integrity - Service - Excellence

Thermal Source Reduction Technologies

U.S. AIR FORCE

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Thermal Technologies

- Steam injection
- Resistive heating
  - 3- or 6-phase heating
- Hot air injection
- Heat wells/blankets
- Radio frequency heating
- Hot water flushing

Recovery Systems

Technology	SVE	GW Extraction
Steam injection	✓✓	✓
Resistive heating		
3- or 6-phase heating	✓✓	
Hot air injection	✓✓	
Radio frequency heating	✓✓	
Hot water flushing		✓✓

Overriding Equation

IF:

A = (Complex lithology)

B = (Complex soil:water:NAPL:vapor interactions)

C = (Complex resistive heating)

D = (Complex heat dissipation)

E = (Complex condensate deposition)

F = (Complex soil conductivity/permeability changes)

G = (Complex vapor recovery)

H = (Complex aboveground treatment and controls)

THEN: A x B x C x D x E x F x G x H = ?

Resistance Heating

- Resistance controlled by electrical conductivity, soil moisture
- These parameters are likely to change significantly over time and space
- Soil moisture supports more efficient resistive heating, but can interfere with effective vapor capture and treatment

Soil Conductivity

- Example:
  - Lower conductivity clay - 29Ù
  - Higher conductivity clay - 2.5Ù
- For a 20 kW power input (100 A):
  - The lower conductivity clay would require a line voltage of 440 V (RMS)
  - The higher conductivity clay would require a line voltage of 115 V (RMS)

Power Delivery

If a sand were to uniformly dry out from s = 5×10^{-3} S/m (18% moisture) to 1×10^{-4} S/m (50x),

Then the resistance would climb by a factor of 51W to 2,600W

For a constant voltage source, the interelectrode current would decrease by the same factor, reducing the power delivered to the soil by a factor of $(51)^2 = 2{,}600$

Power Dissipation

- 50% of power dissipated within 5 inches of electrodes
- 8% within carbon particle-filled annulus surrounding each electrode
- "Rapid soil drying of the soil would be expected with a corresponding significant increase in R_{total}, and this was observed." (Dablow et. al. 2000)

Power/Heat Dissipation

- Mineral encrustation of irrigated electrodes caused a decrease in electrical power transfer (Dablow et. al. 2000)
- Heating vs. vapor capture area
  - Practitioners estimate that heating extends to approximately 140% of the electrode array area

Steam Generation

- In situ:
  - Resistive heating & Hot air injection
    - Vadose zone: 40 - 90L H_20/m^3 soil
    - Saturated zone: 200 - 400L H_20/m^3 soil
- Ex situ:
  - Steam injection
- Latent heat of vaporization of water [2.45MJ/L])

Vapor Capture

- The subsurface is an excellent heat exchanger
- Steam condensate will be formed between any steam generation point A and point B where soil temperatures are < 100°C
- Air permeability is reduced to near zero in areas of high water saturation (e.g. <60%)
- "Flash" volatilization instantaneously creates large increases in volume

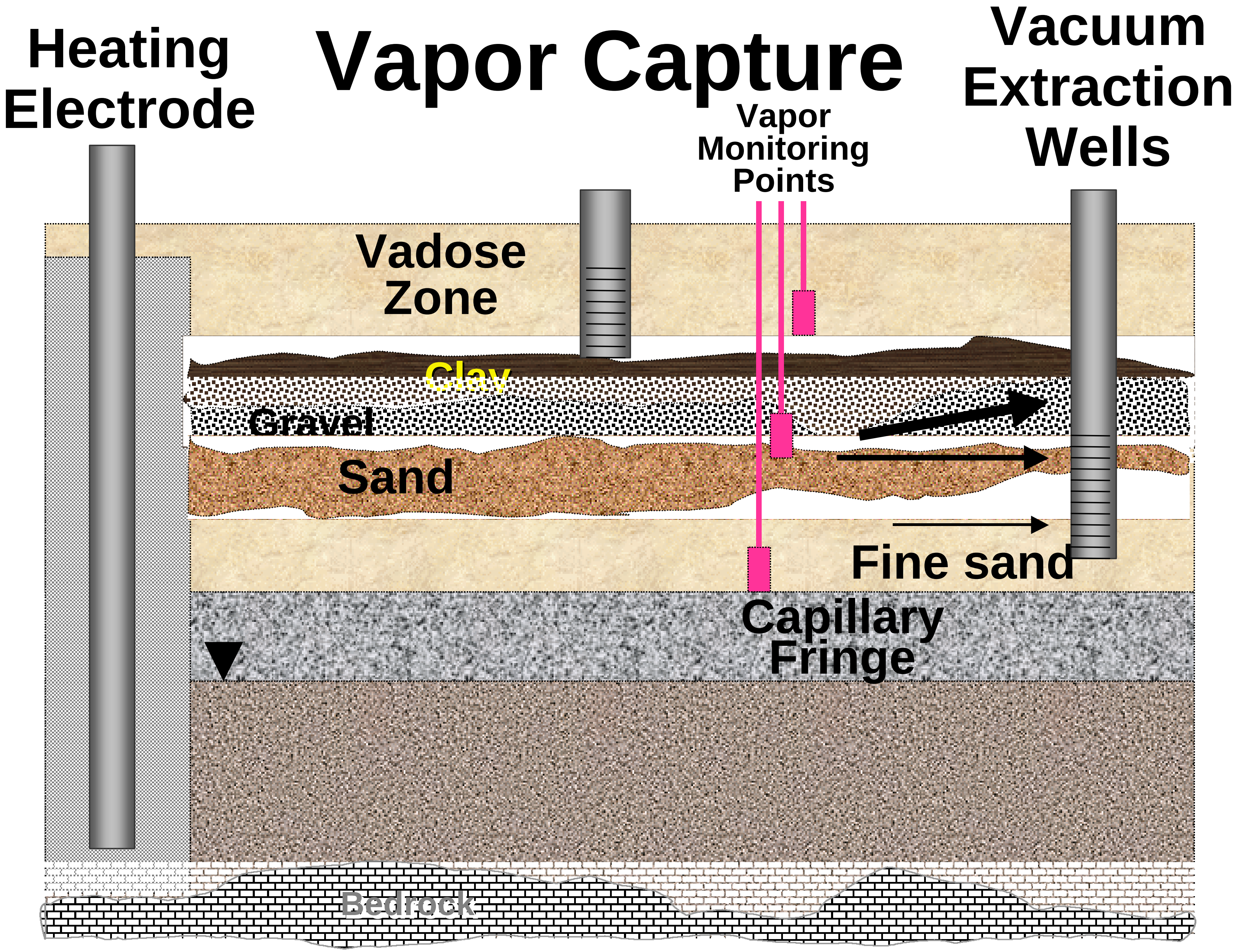
Tracer Recovery Tests

- Essential to vapor capture efficiency evaluation
- Air Force Plant 4 -
  - Helium recovery tests resulted in 3 - 92% He recovery prior to heating
  - Two helium injection points within screened interval of SVE wells
  - One helium injection point 2- 3 feet below SVE well = lowest recovery
  - Problem quantifying He in “hot, humid” stream
  - Did not evaluate total recovered

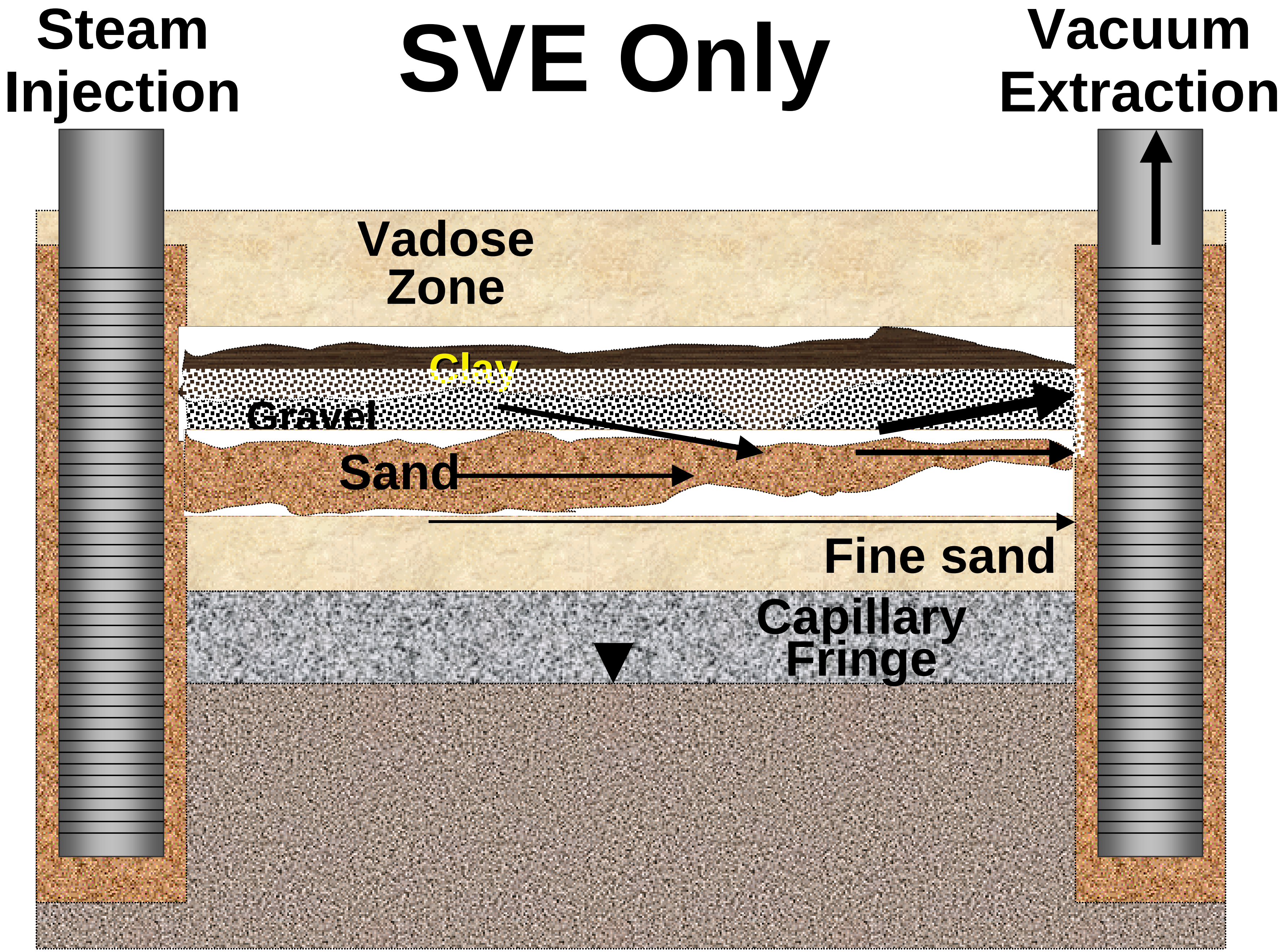
Helium Recovery

Monitoring Point	Extracted Gas Flowrate (SCFM)			Helium Recovery (%)		
	Baseline	Week 4	Week 9	Baseline	Week 4	Week 9
TA-12	13.8			25		
Main Header	111.9			92		
VR-3d	15.3	12.1	13.7	37	55	58
Main Header	111.7	120.1	163.3	45	87	74
TA-13		12.4	16.8		22	80
Main Header		122.1	163.3		88	105
VR-2s	7.0			3		
Main Header	112.1			69		
VR-2d		10.1	10.5		161	259
Main Header		118.4	165.1		120	96

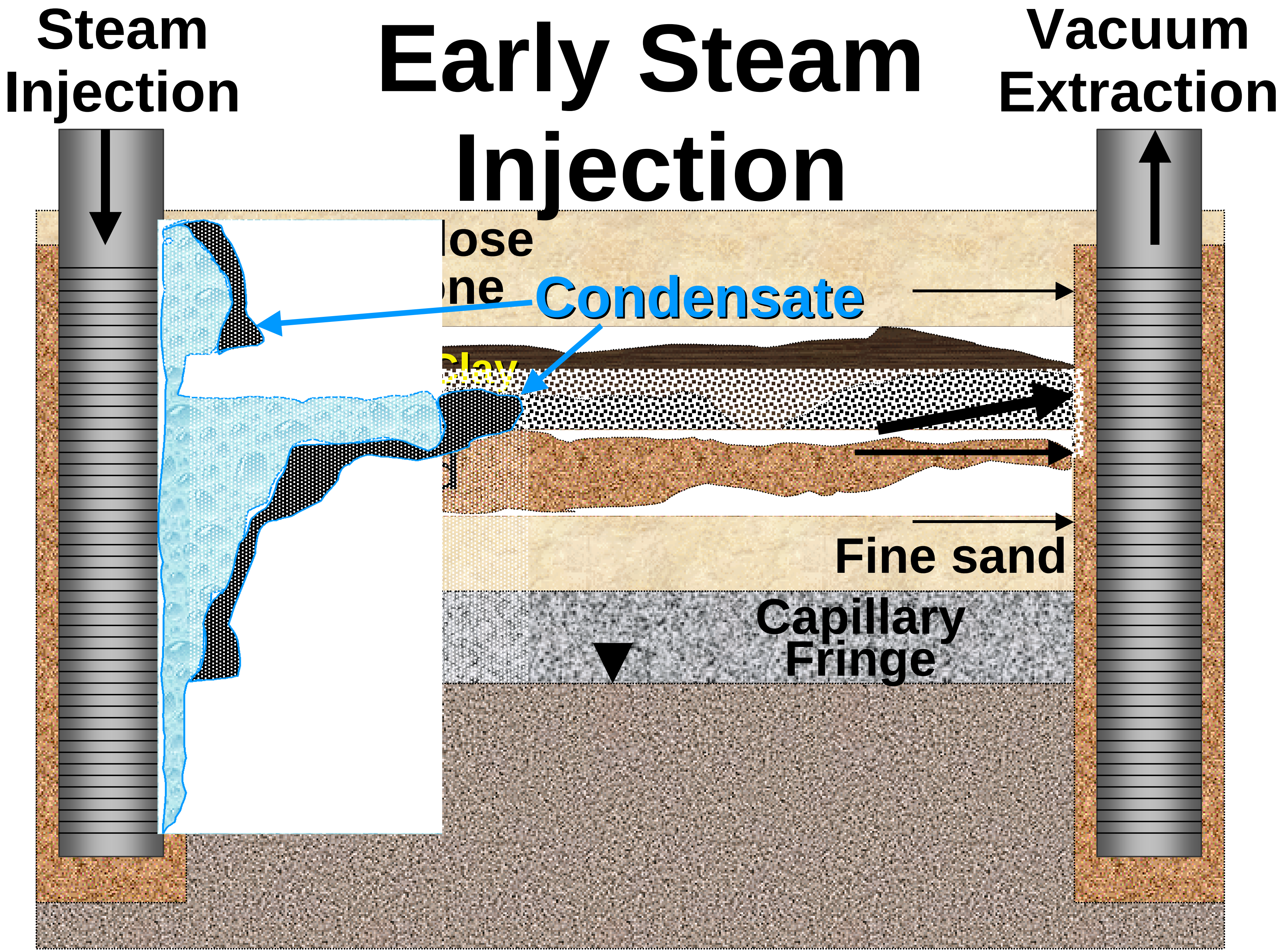
Vapor Capture



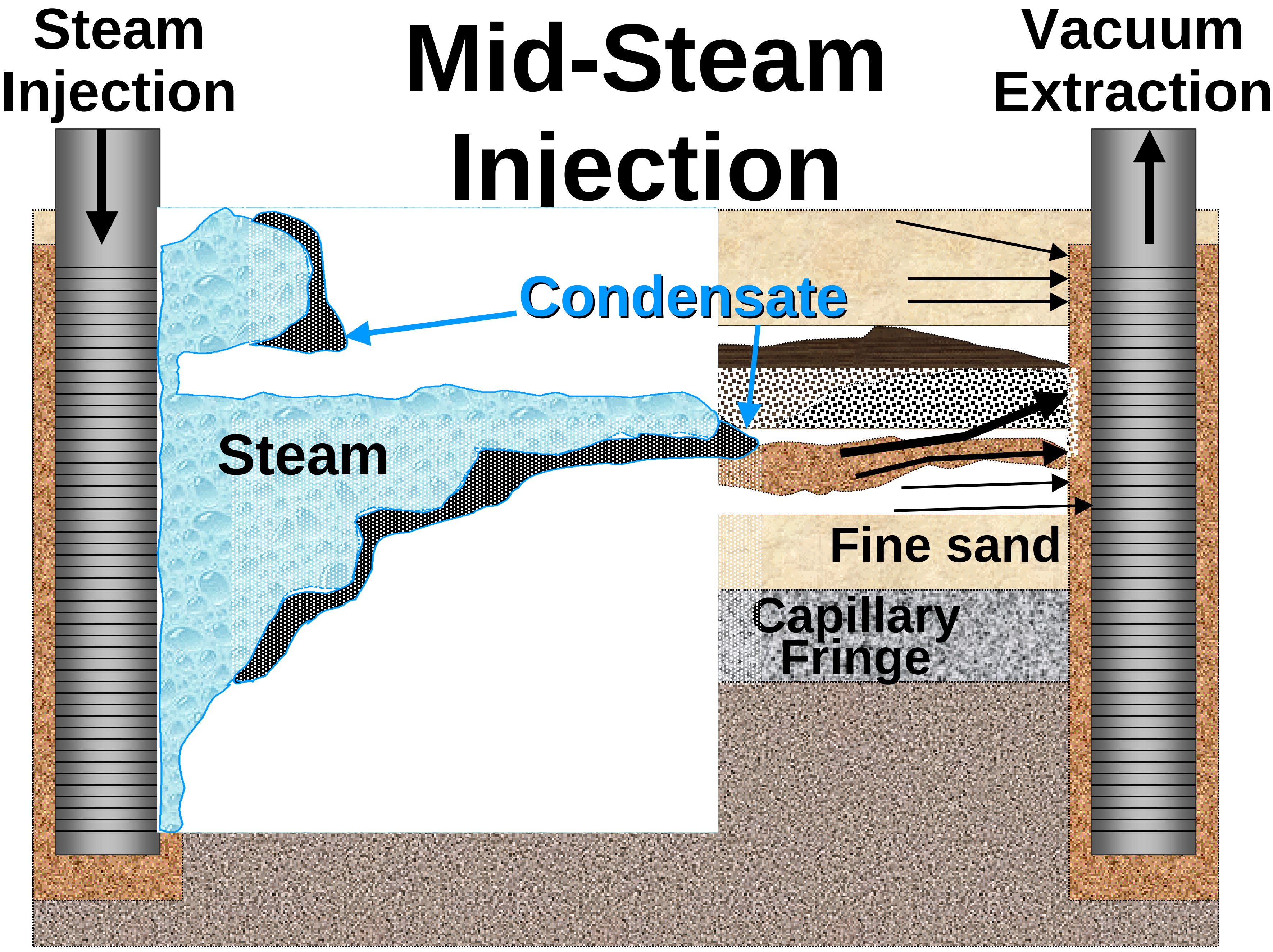
SVE Only


Steam
Injection
Vacuum
Extraction
Vadose
Zone
Clay
Gravel
Sand
Fine sand
Capillary
Fringe

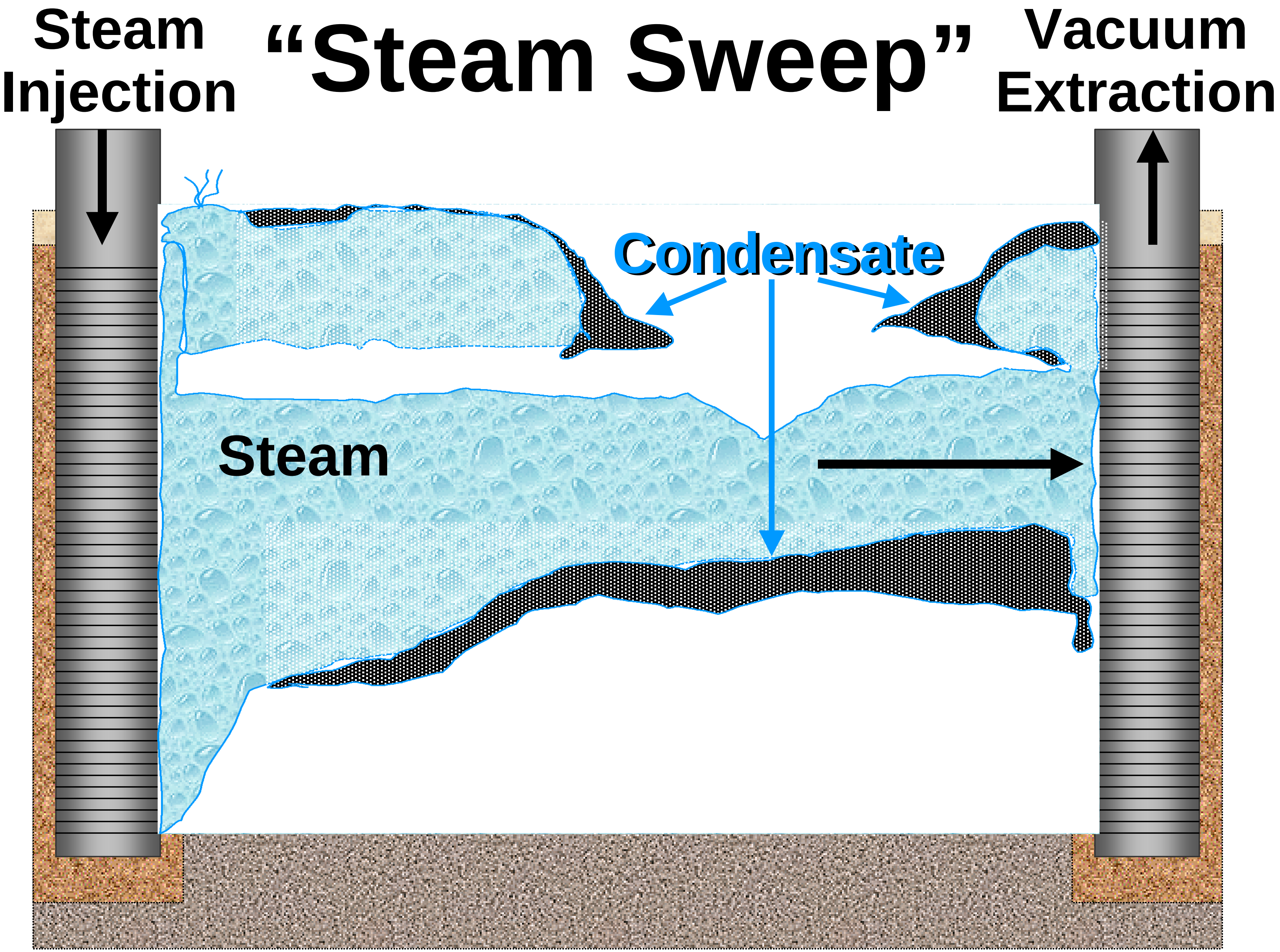
Early Steam Injection



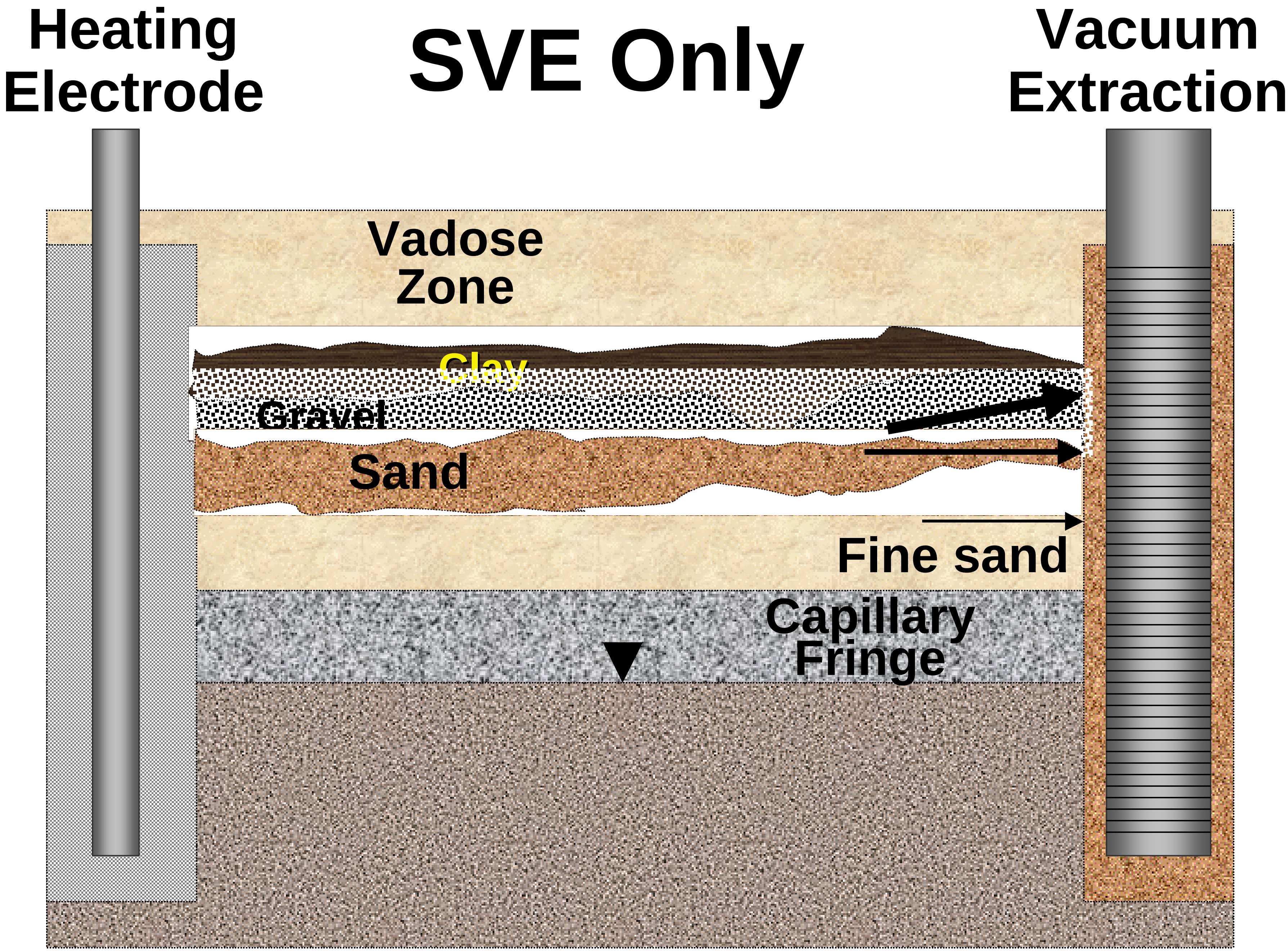
Mid-Steam Injection



“Steam Sweep”



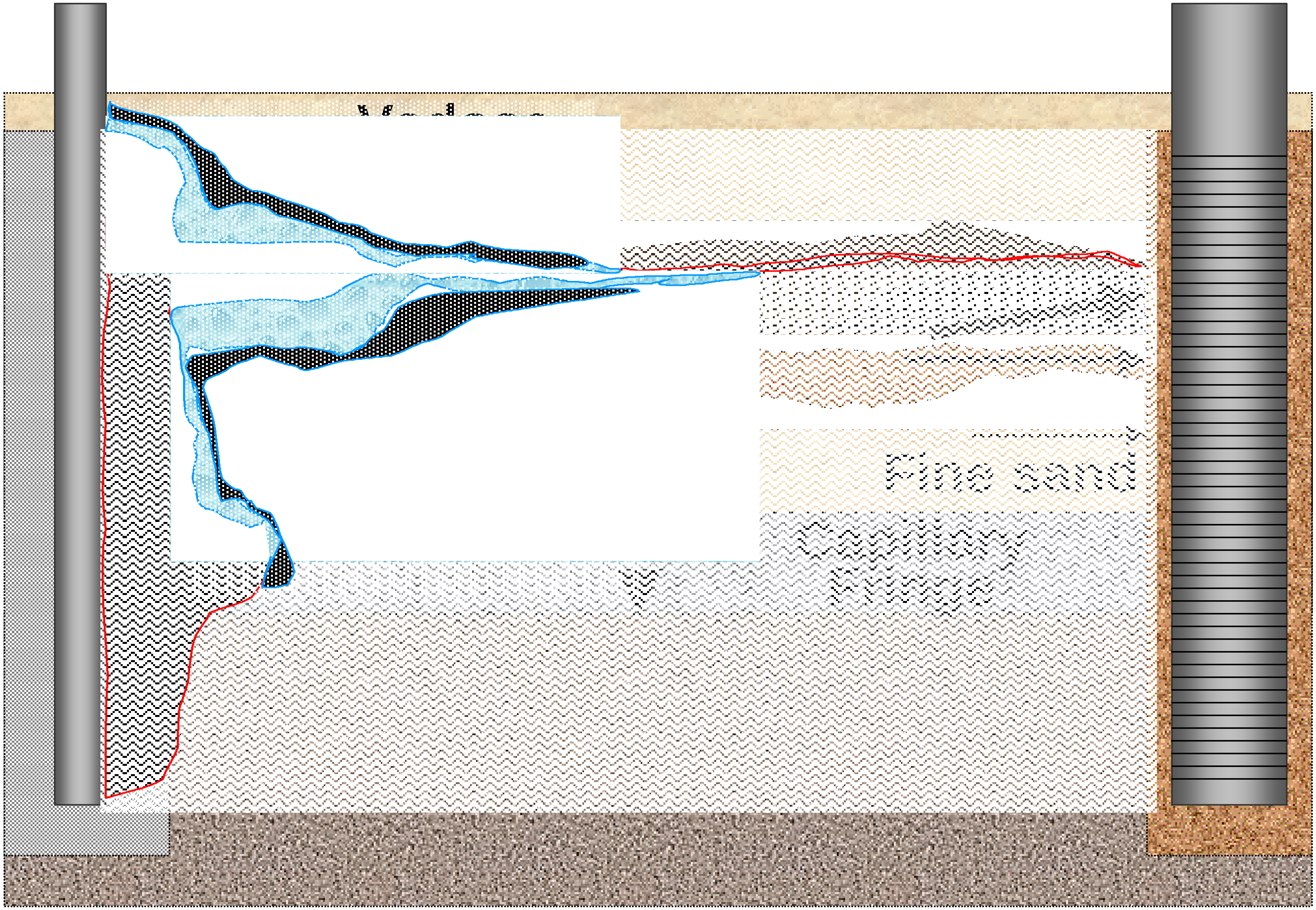
SVE Only


Heating Electrode
Vacuum Extraction
Vadose Zone
Clay
Gravel
Sand
Fine sand
Capillary Fringe

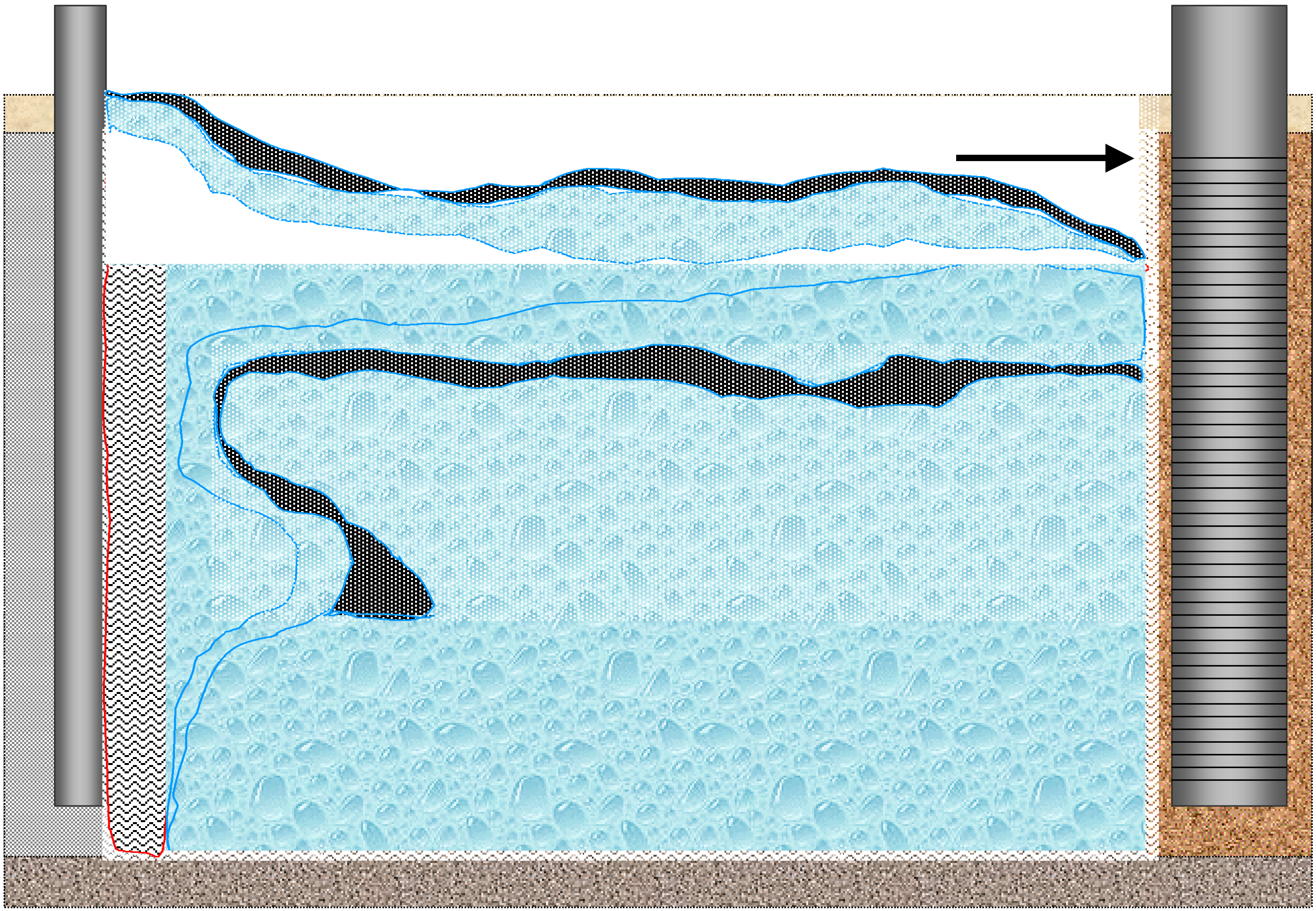
Early Heating

Heating Electrode

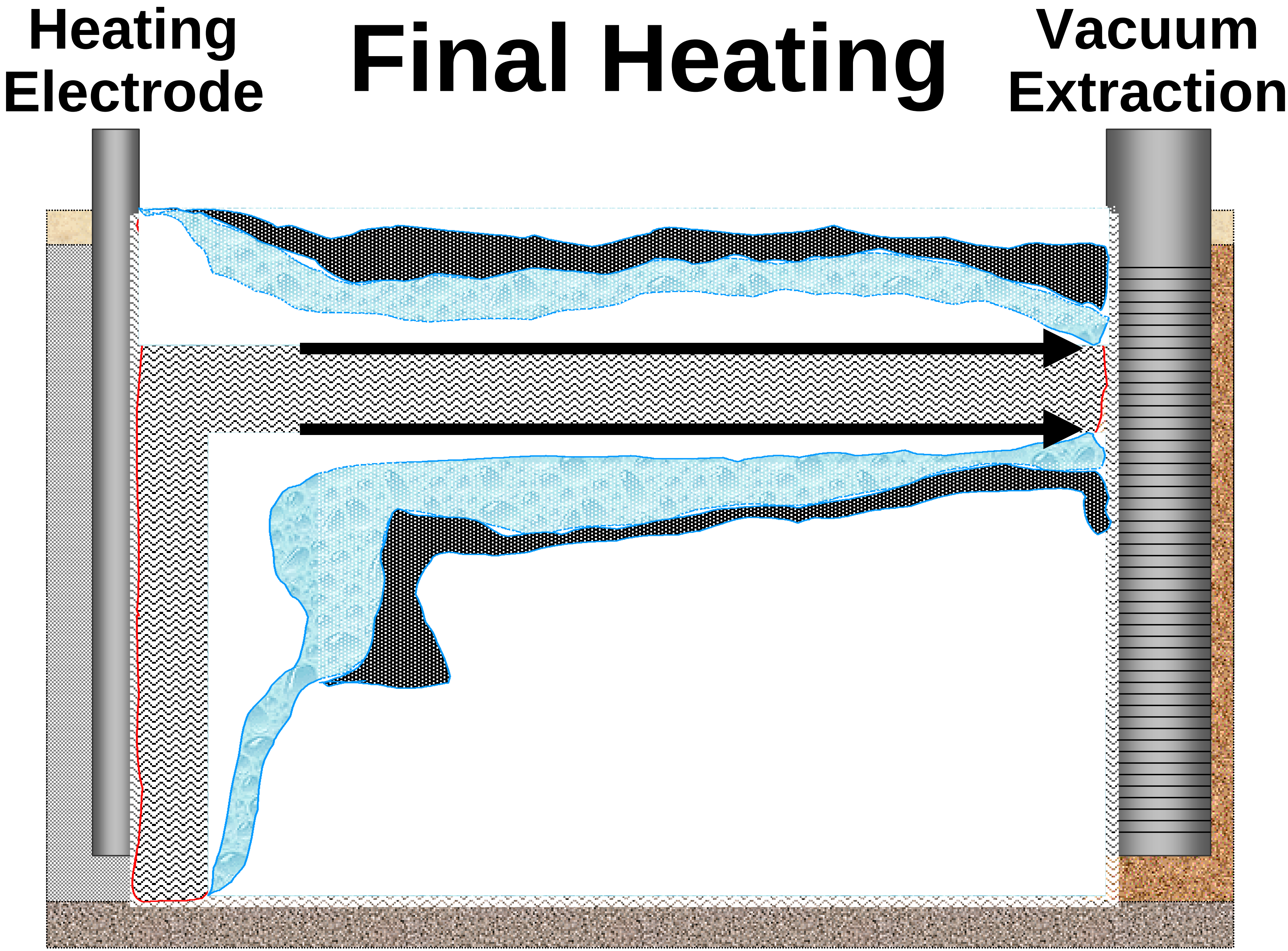
Vacuum Extraction



Mid-Heating



Final Heating



Other Issues

- Viability of modular approach
- Compatibility with on-site utilities
- Fugitive emissions
- Degree of mass removal - Enough?
- Risk to on-site workers
- Site characterization requirements to implement and evaluate
- Availability of specialized equipment
- How to collect representative samples

Costs

- How much do you have to spend?
- Very site-specific
  - Site complexity
  - Saturated zone impacts
  - Energy costs
  - $50 - 300/yd^3

Summary

- Use of thermal remediation increasing
- Capture of mobilized contaminant is the area of greatest concern
- Application to DNAPL impacted saturated zones appears particularly problematic
- Performance evaluation requires more consistent and rigorous testing methodologies

Summary

- Resistive heating may be more advantageous at silt or clay sites - Unique niche
- Modular approach common
- More sophisticated tracer and recovery tests would significantly improve safety and performance evaluation
- Buyer beware!

References

Balshaw-Biddle, K.; Oubre, C. L.; Ward, C. H. (Editors): Dablow, J. F.; Johnson, P. C.; Pearce, J. A. (Authors). 2000. Steam and Electroheating Remediation of Tight Soils. Lewis Publishers, Boca Raton.