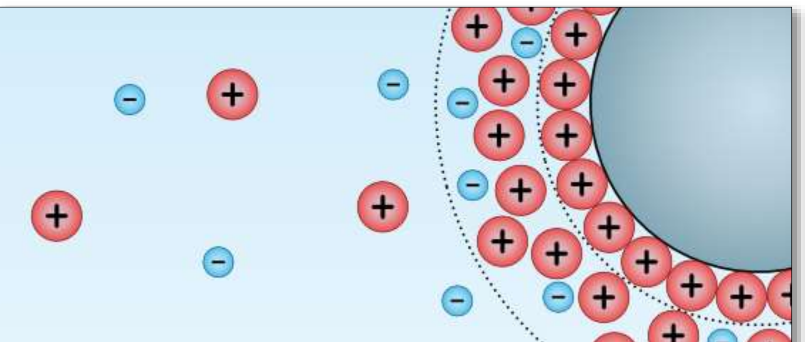
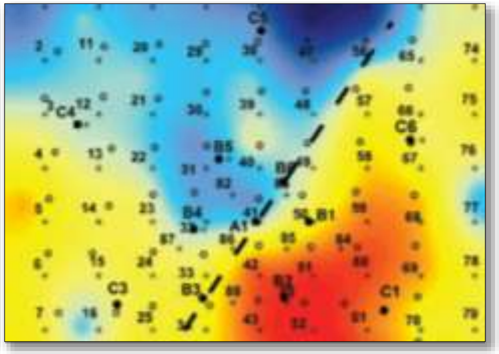
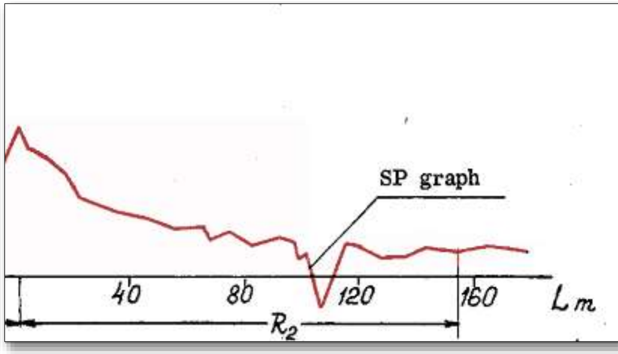
Exceptional service in the national interest

Sandia National Laboratories





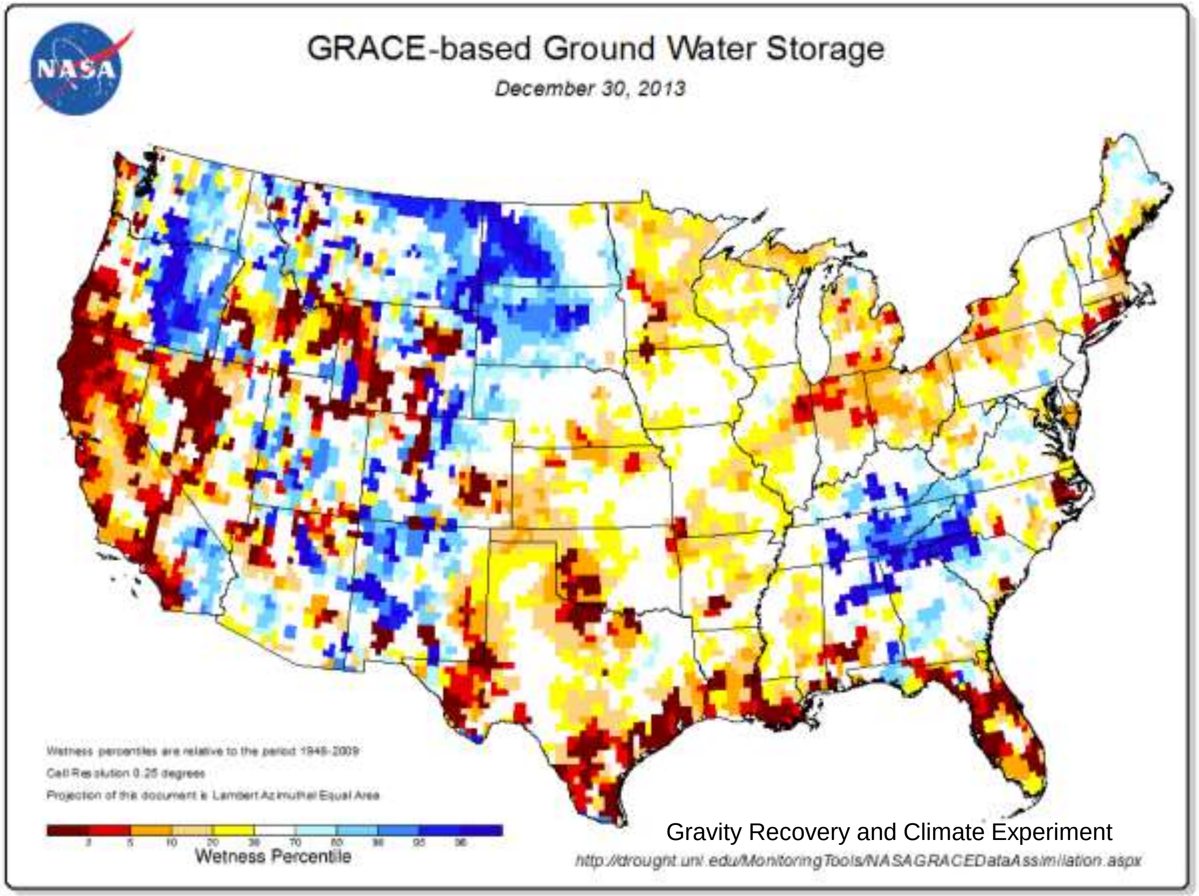


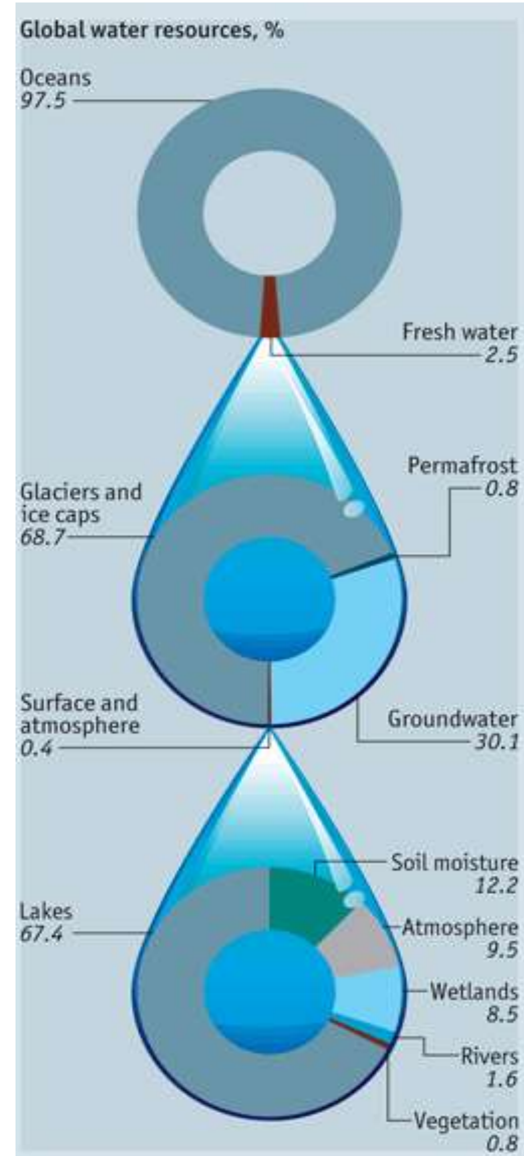
Seeing into the Earth with Hydrogeophysics: Streaming Potential

Kristopher L. Kuhlman

Sandia National Laboratories, Applied Systems Analysis & Research Dept.

Groundwater Importance

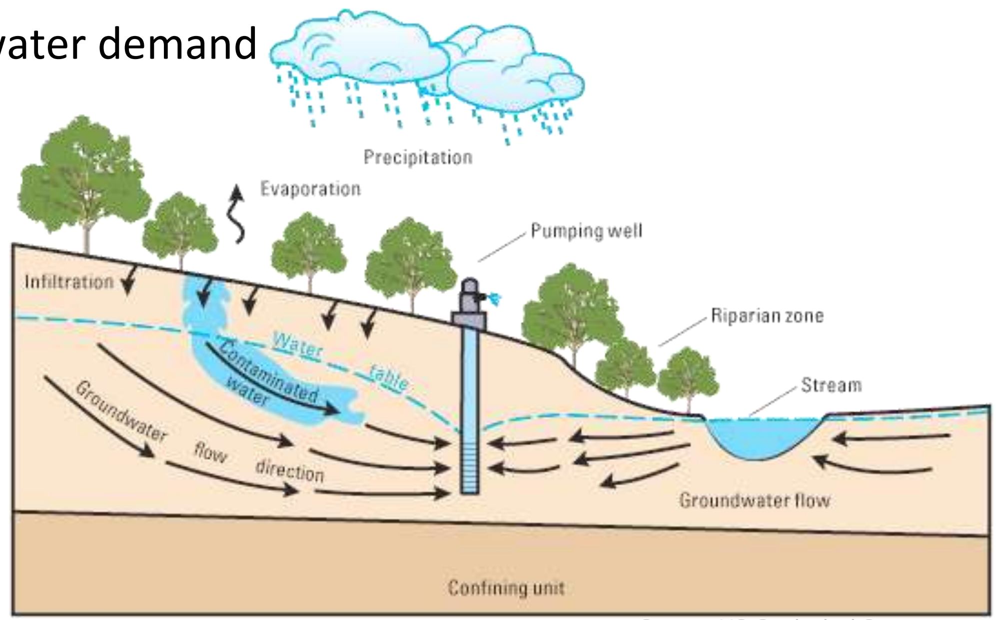




Source: economist

Groundwater Flow and Transport

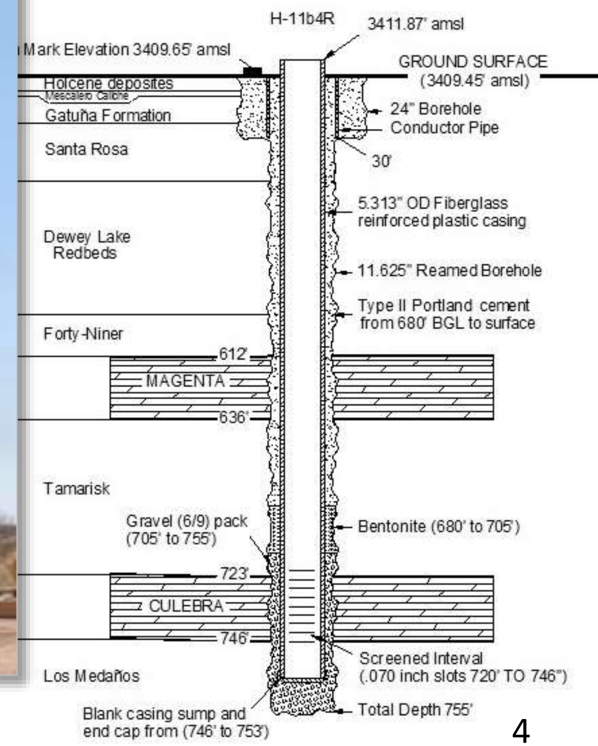
- Groundwater flow
  - Is there enough water?
    - Meeting growing municipal water demand
    - Water rights / litigation
  - What is source of water?
    - Precipitation or infiltration
    - Old water from storage
- Solute transport
  - Will contaminant migrate?
    - South Valley contamination
    - Kirtland AFB jet fuel spill
  - Can we clean up contamination in our lifetime?
  - Complexities and heterogeneities critical to transport



Source: US Geological Survey

Wells are Important & Expensive

- Wells are primary access points to groundwater
  - *Can't measure pressure (system state) remotely*
- Expensive to drill/complete/maintain (often >$100k)



Geophysics to the Rescue!

- Allows us to "see into the Earth"
- Cheap/easy fields to measure at surface
  - Electromagnetic fields
  - X, Y & Z acceleration (seismic)
  - Gravitational field (microgravity)
- Empirical petrophysical relations:
  - Geophysical properties ↔ Hydraulic properties

e.g., Archie's Law

$$\sigma_{\mathrm{t}} = \tau \sigma_{\mathrm{f}} \phi^{-m} S_w^{-n}$$

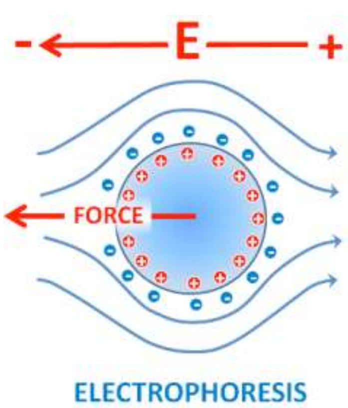
m = "Cementation exponent"
n = "Saturation exponent"

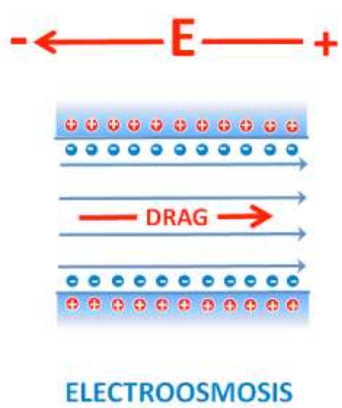
- Hydrogeophysical methods:
  - Geophysical state variables ↔ Hydraulic properties

Spontaneous Potentials

Voltage → Forces

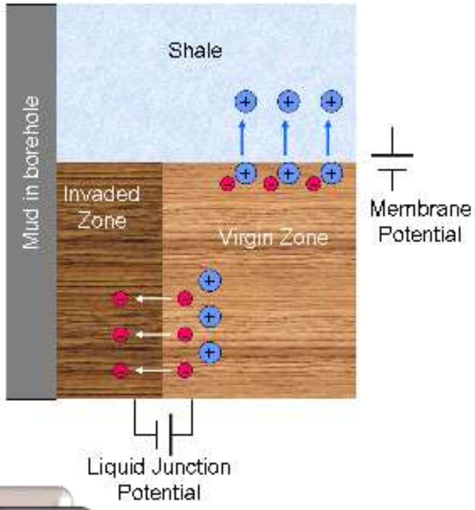
- Electrokinetic Forces
  - Electro-phoresis (particles)
  - Electro-osmosis (pumping)





Process → Voltage

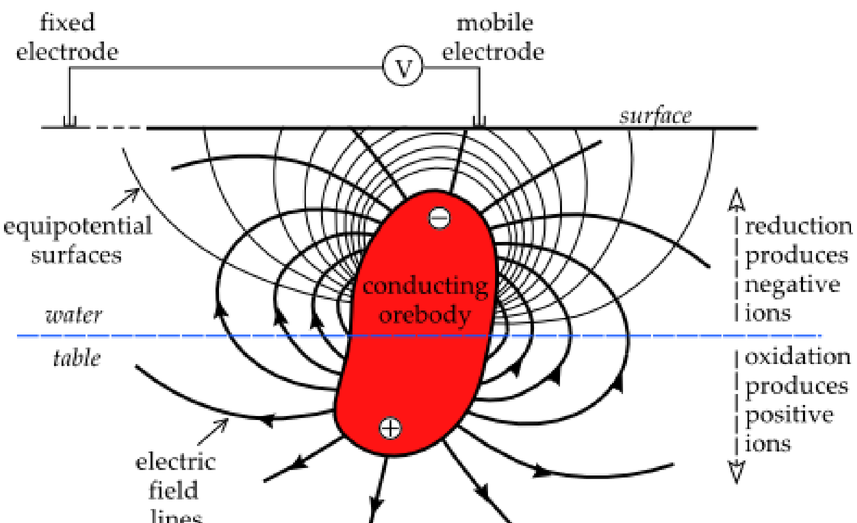
- Spontaneous (self) Potentials
  - **Streaming (Electrokinetic) Potential**
  - Bioelectric Potentials
  - Thermoelectric Potentials
  - Electro-chemical Potentials
    - Diffusion Potential (conc. Gradient)
    - Liquid Junction Potential (waters)
    - Membrane Potential (rocks)
    - Mineralization Potentials (redox)



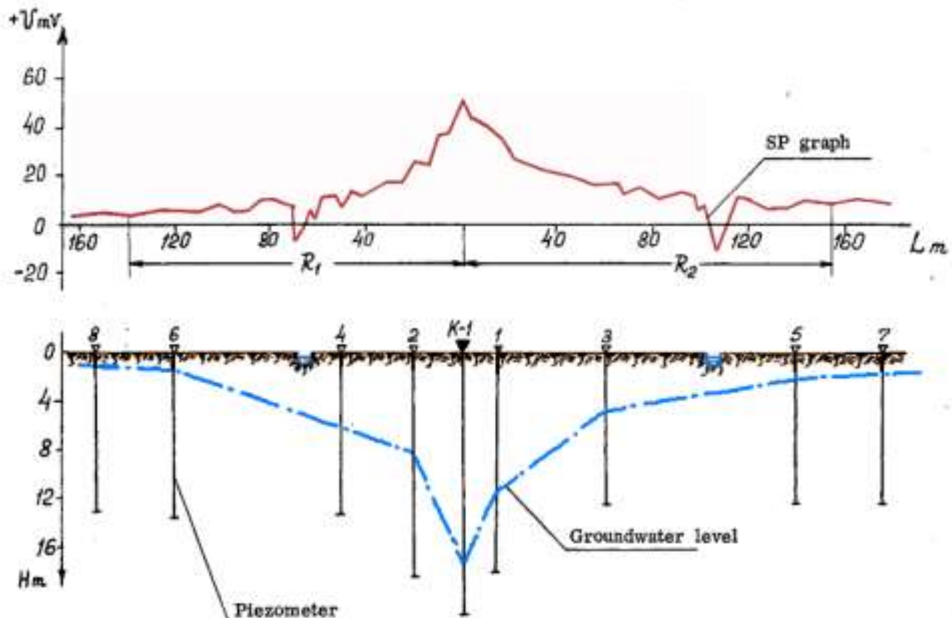
Source: wikipedia

Self Potentials (Historical)

- Static ore bodies (membrane/mineralization potentials)
  - 0.1 to 10 Volts
- Transient pumping/recharge (electrokinetic potential)
  - 0.01 to 1 Volt

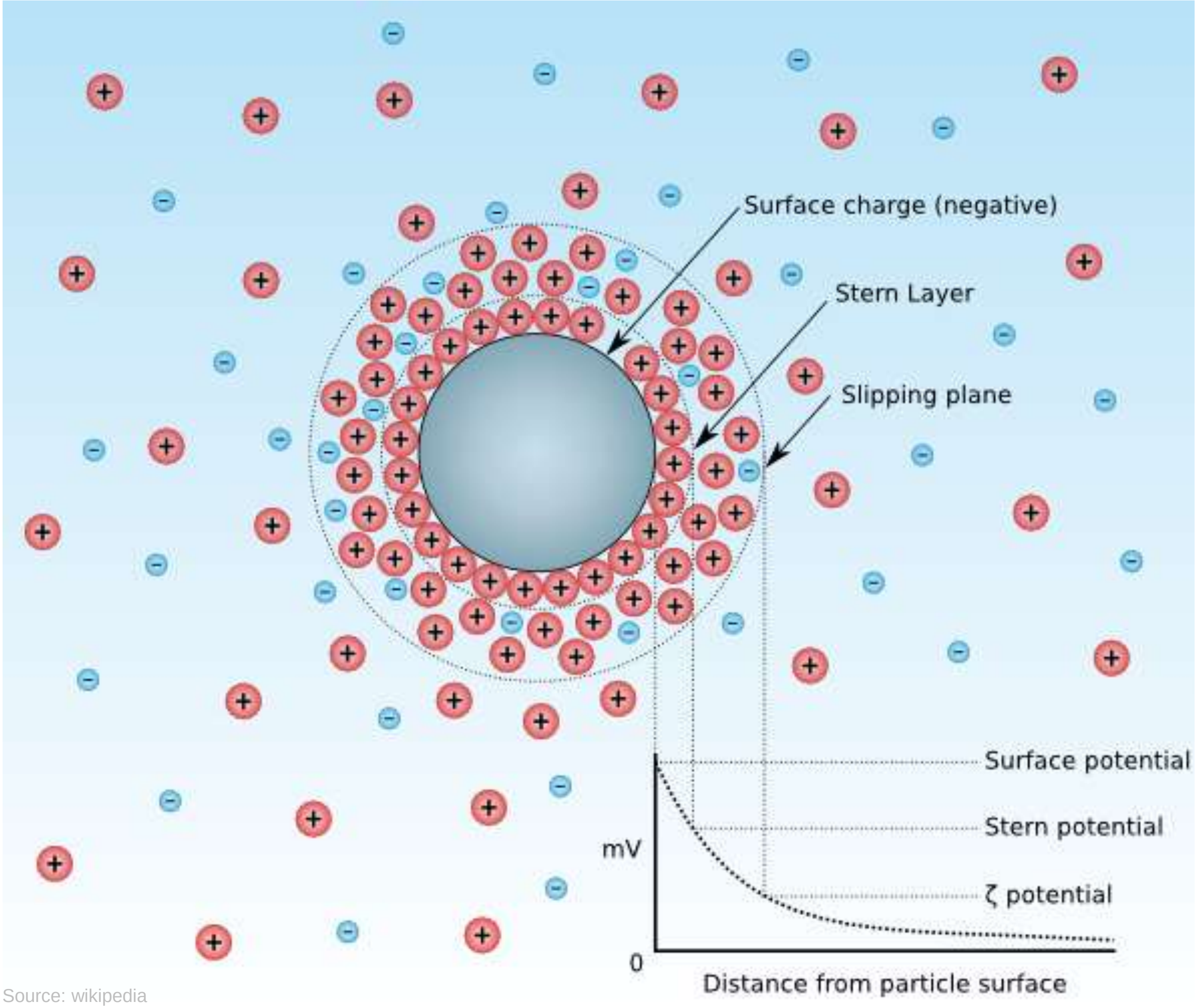


Modified from Lowrie (2007)



Bogoslovsky and Ogilvy (1972)

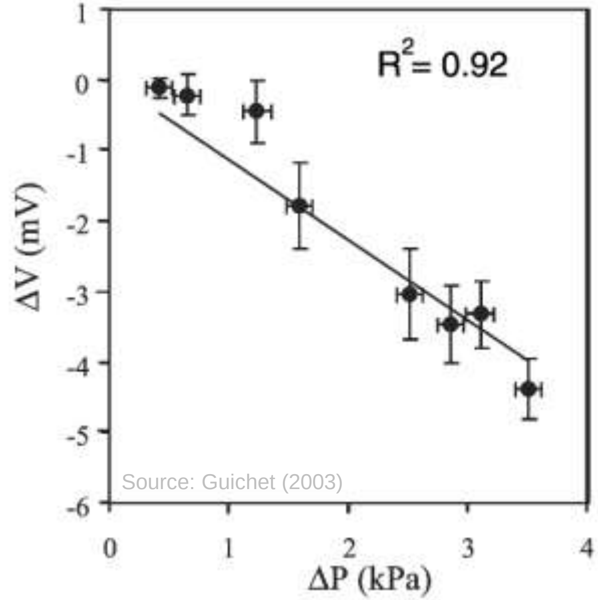
Static Ion Arrangement



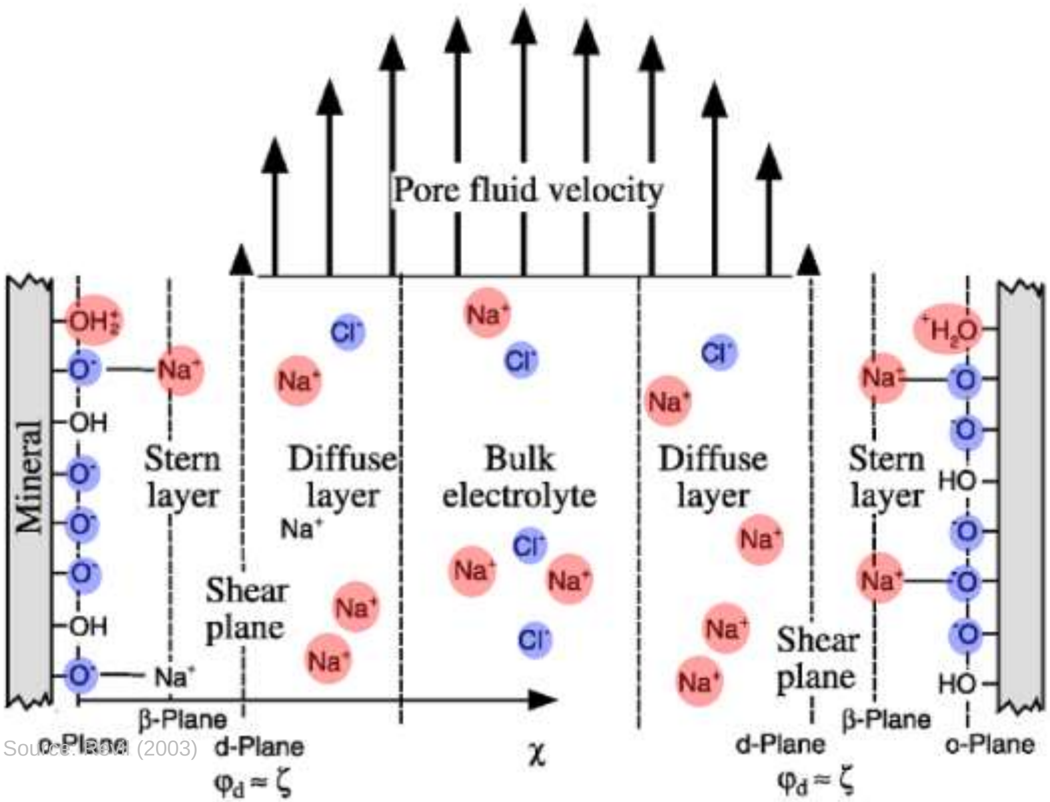
Source: wikipedia

Foundation of SP in porous media

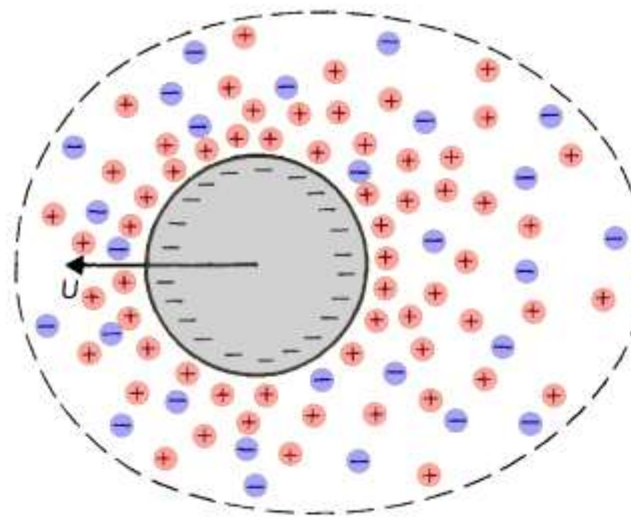
- Moving electrolytes ⟶ voltage
- Bulk/Diffuse layer flow (1D)
- Double-layer becomes distorted (2D/3D)



Source: Guichet (2003)



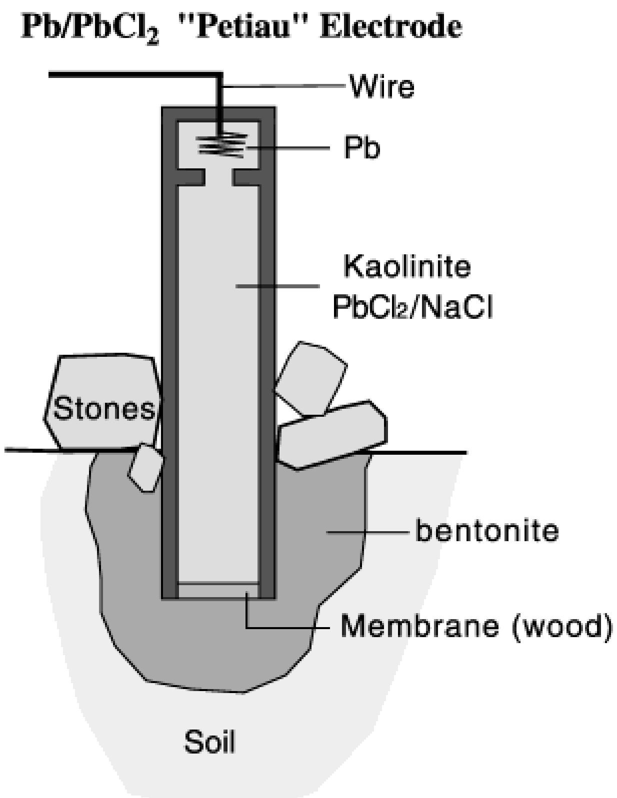
Source: [illegible] (2003)



Source: Probstein (1994)

SP Voltage Sensors

- High-impedance voltmeter
- Non-polarizable single-ended electrodes
  - Environmental: $Pb/PbCl_2$
  - Biomedical: Ag/AgCl
- Reference electrode
- Electrode development work in Carlsbad (2013 patent application)

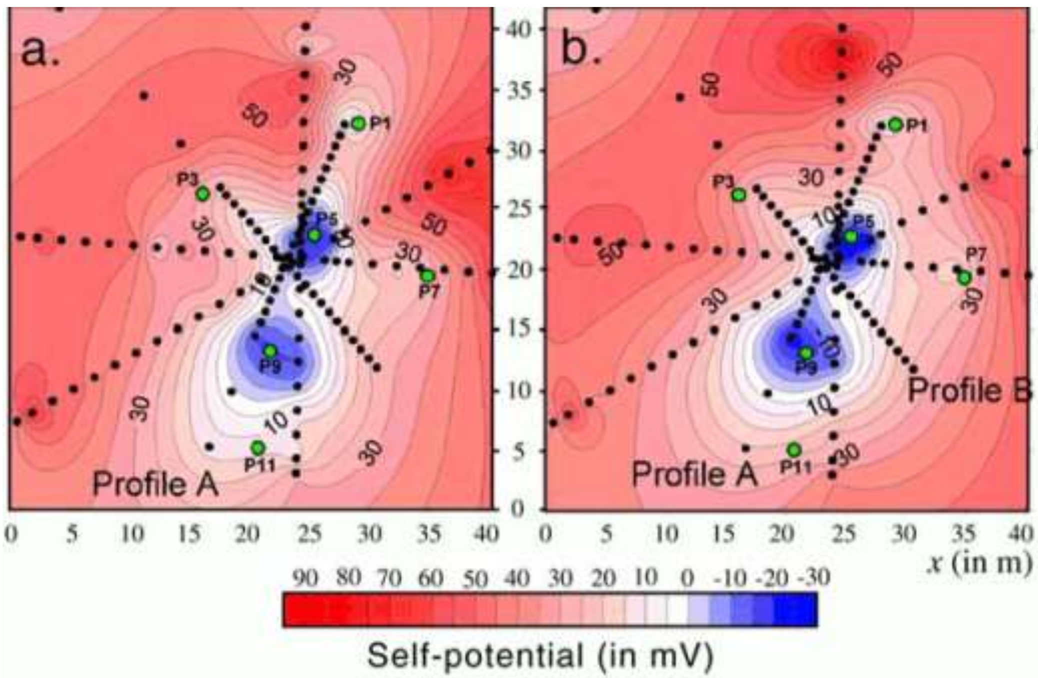


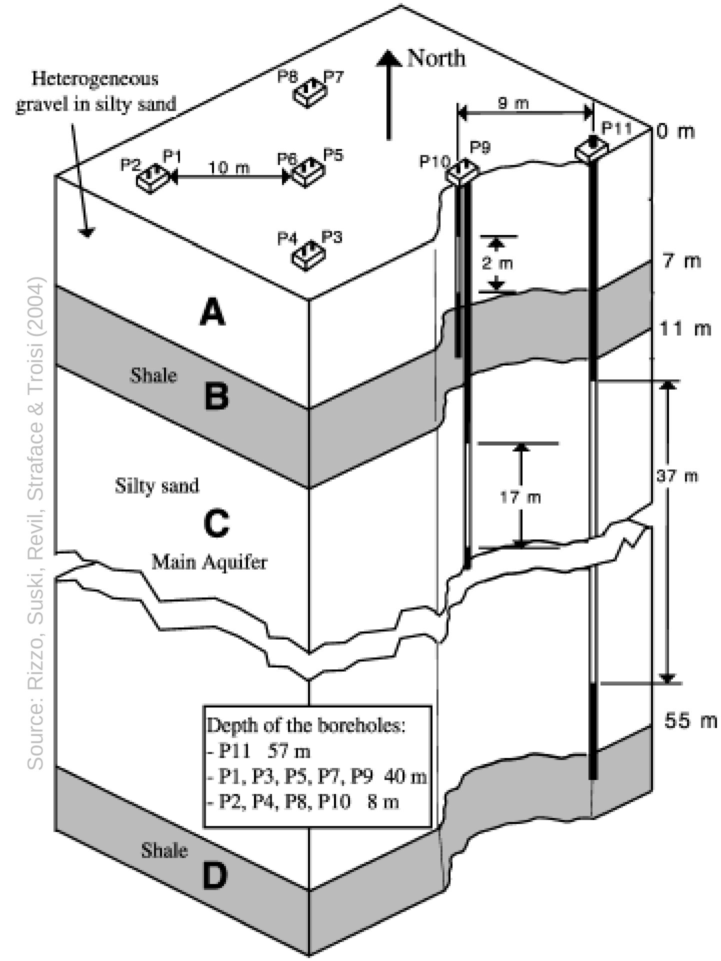
Field Examples

SP Field Test (S. Italy)

- Pumping test analysis with SP. Rizzo et al (2004)
- Steady-state post-pumping only
- Qualitative analysis

Pumping Recovery





Source: Rizzo, Suski, Revil, Straface & Troisi (2004)

SP/Flow Mathematical Model

- Physics-based model of coupled processes

Darcy's law / electro-osmosis

Darcy's flux $$\vec{q} = \frac{k}{\nu}\left(\nabla p - \rho_f \vec{g}\right) - \sigma C \nabla \varphi$$

Current flux $$\vec{j} = \sigma C \left(\nabla p - \rho_f \vec{g}\right) + \sigma \nabla \varphi$$

electro-kinetic / Ohm's law

- Conservation equations

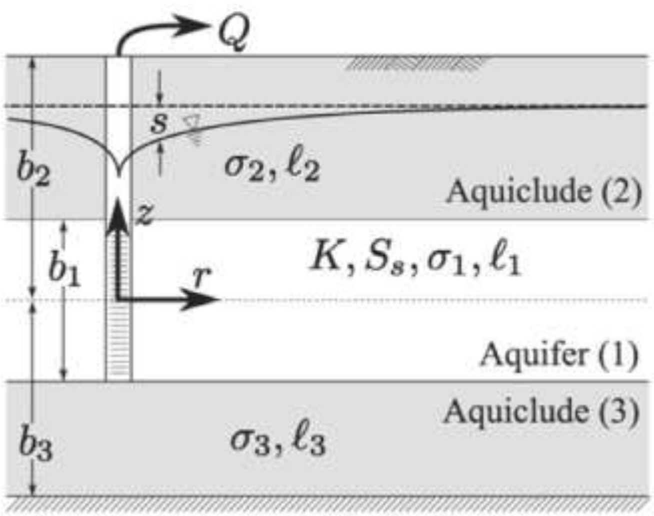
Charge conservation $$\nabla \cdot \vec{j} = 0$$

Mass conservation $$\nabla \cdot \vec{q} = S_s \frac{\partial p}{\partial t}$$

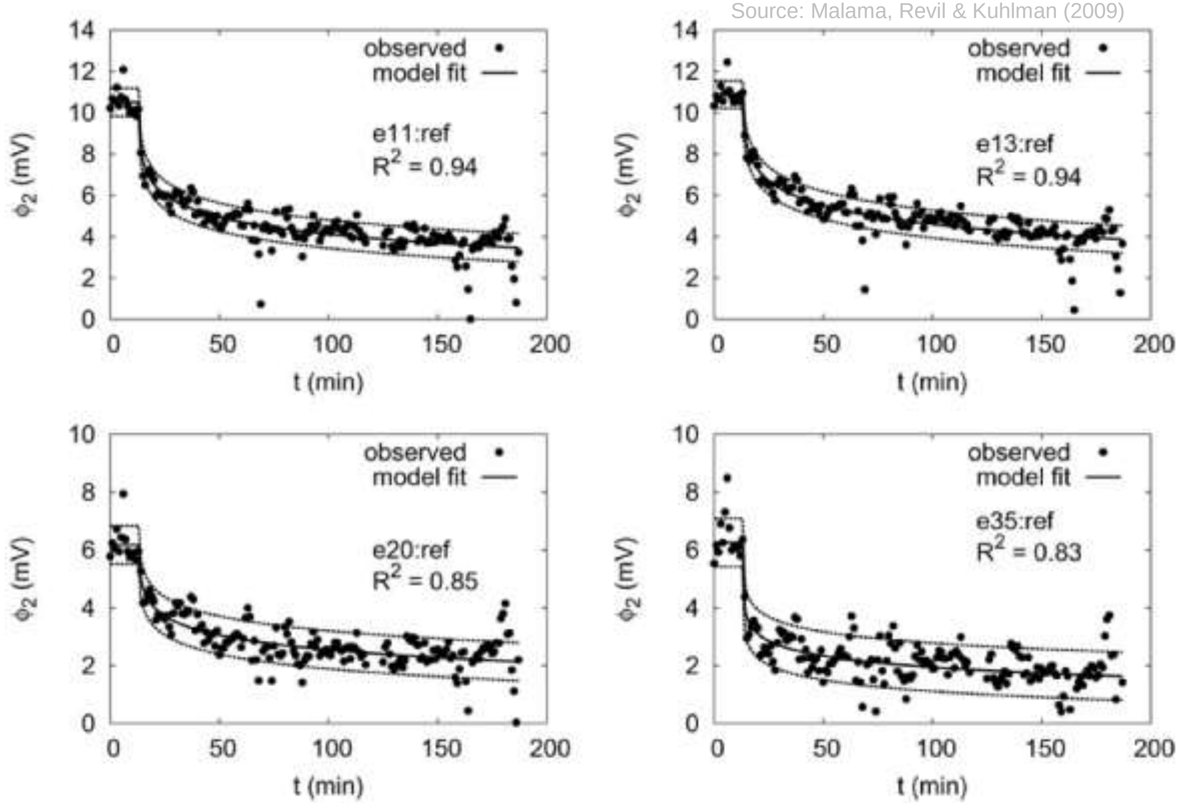
- If no electro-osmosis: solve for flow problem, insert into electrical problem as source term.

SP Field Test (S. Italy)

- Data fit using Malama, Revil & Kuhlman (2009) model
- Estimated aquifer electrical/flow properties from SP response



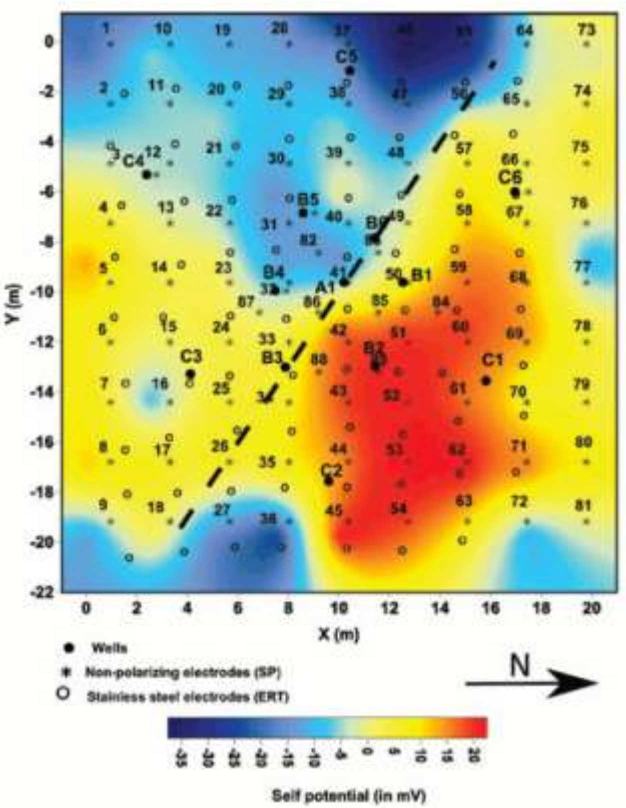
Source: Malama, Revil & Kuhlman (2009)

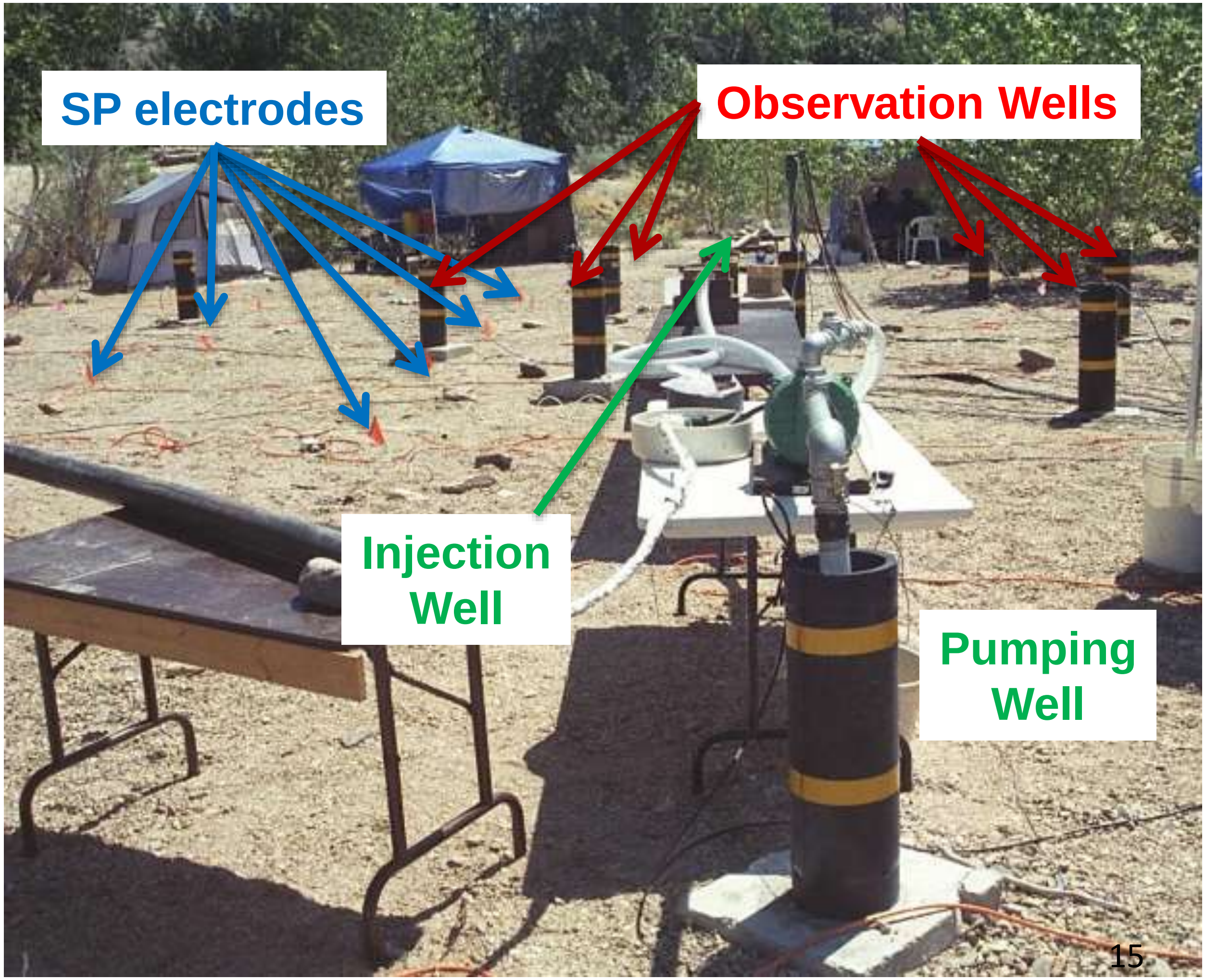


SP Field Test (Boise)

- Unconfined test site along Boise River (Boise State Univ.)
- Dipole pumping test
- Dense network

Source: Malama, Kuhlman & Revil (2009)



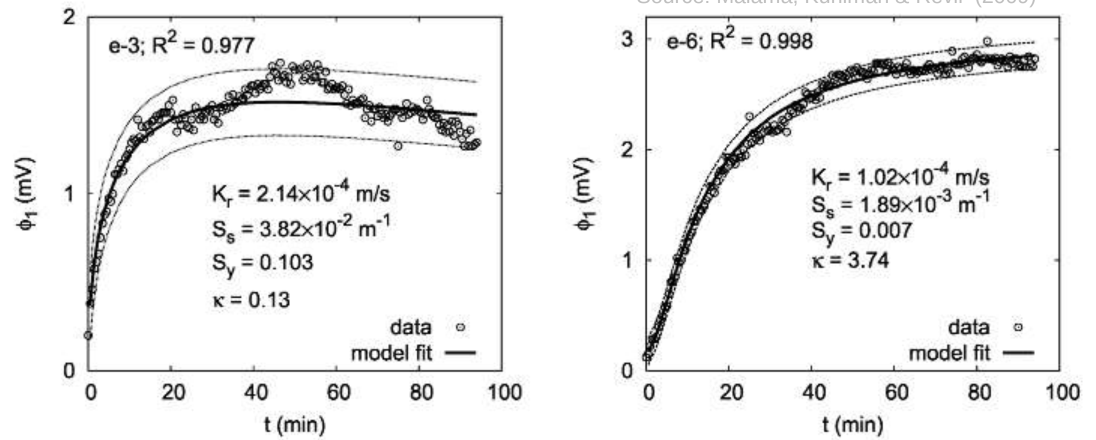


SP Field Test (Boise)

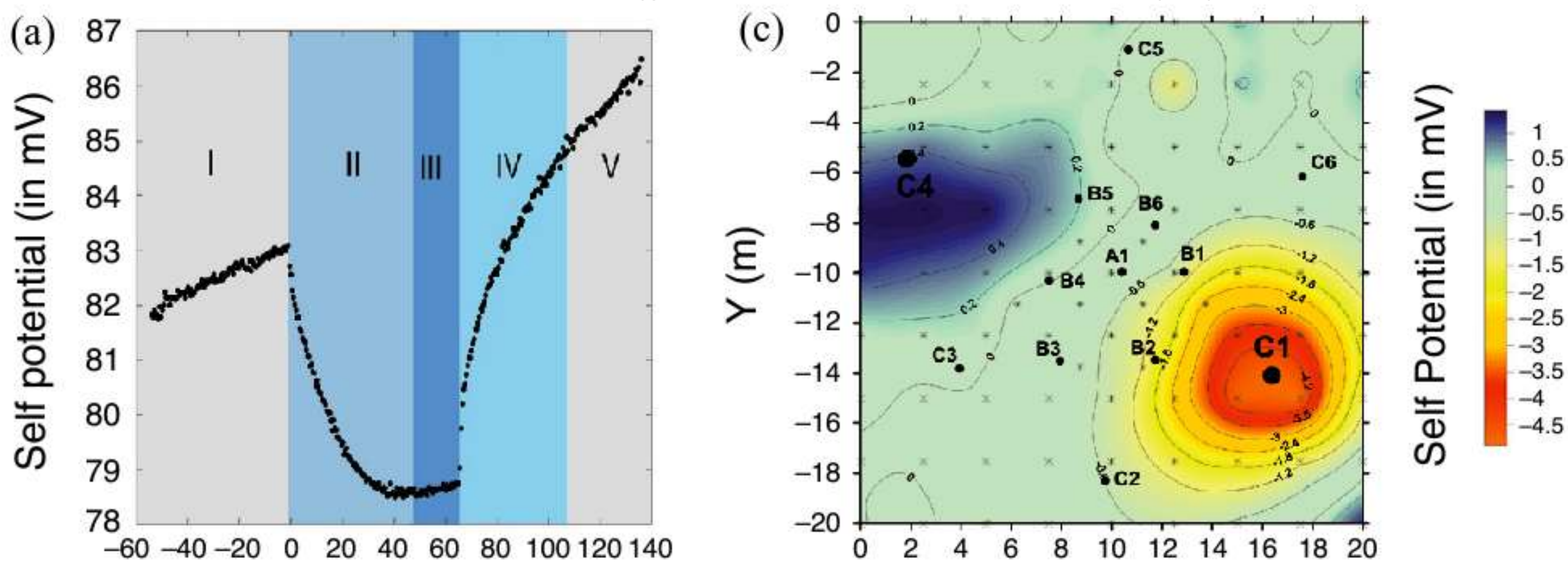
Sandia National Laboratories

- Updated SP model for unconfined systems
- Matched entire transient dataset (not just recovery)
- Estimated unconfined aquifer properties from SP data

Source: Malama, Kuhlman & Revil (2009)

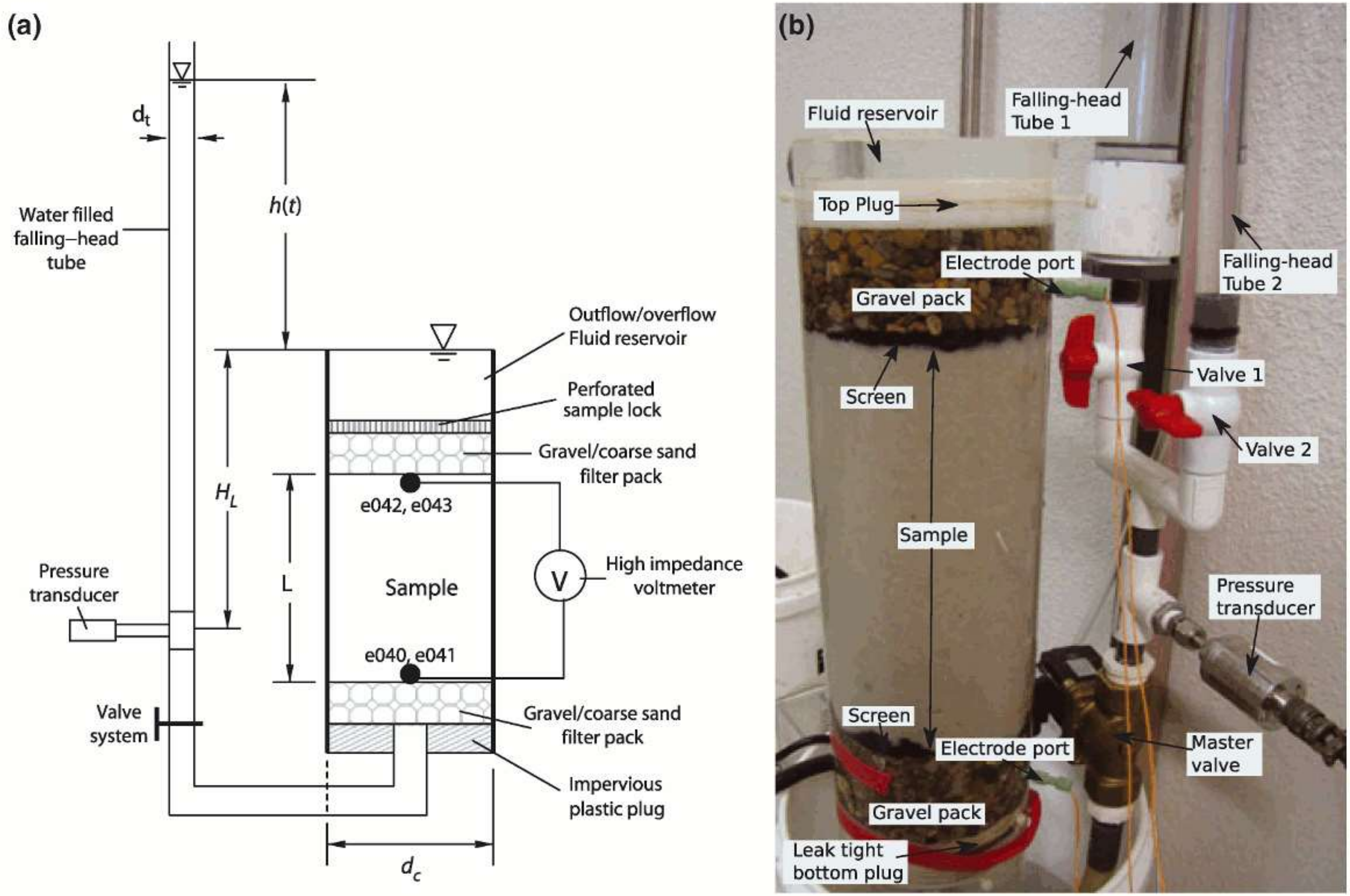


Source: Jardani, Revil, Barrash, Crespy, Rizzo, Straface, Cardiff, Malama, Miller & Johnson (2009)



Lab Examples

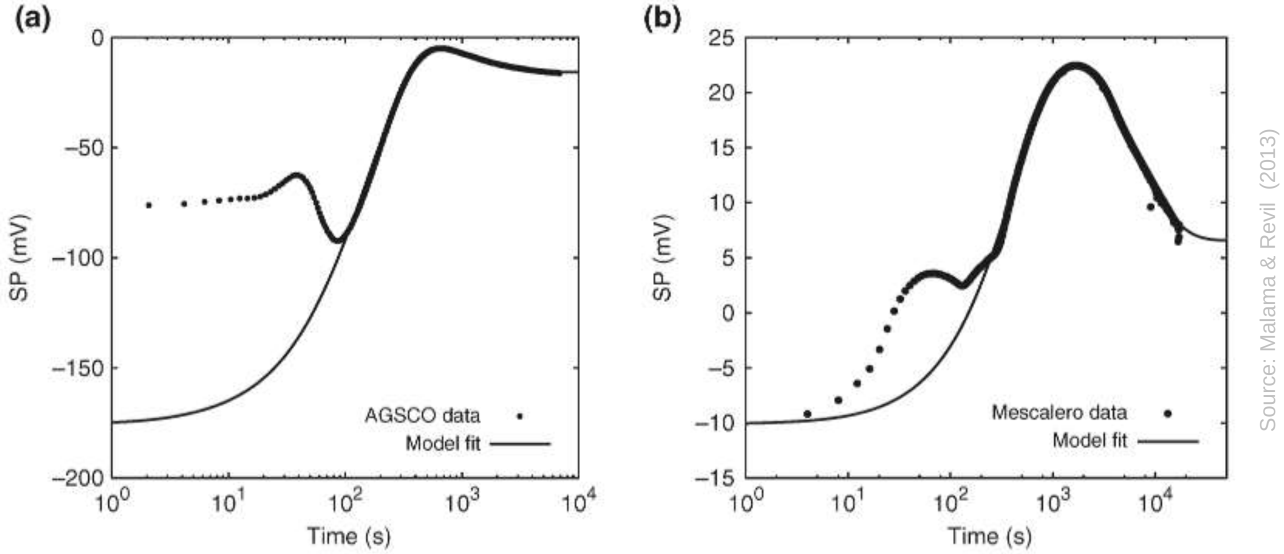
SP Falling-Head Permeameter



Source: Malama & Revil (2013)

Sandia SP Permeameter

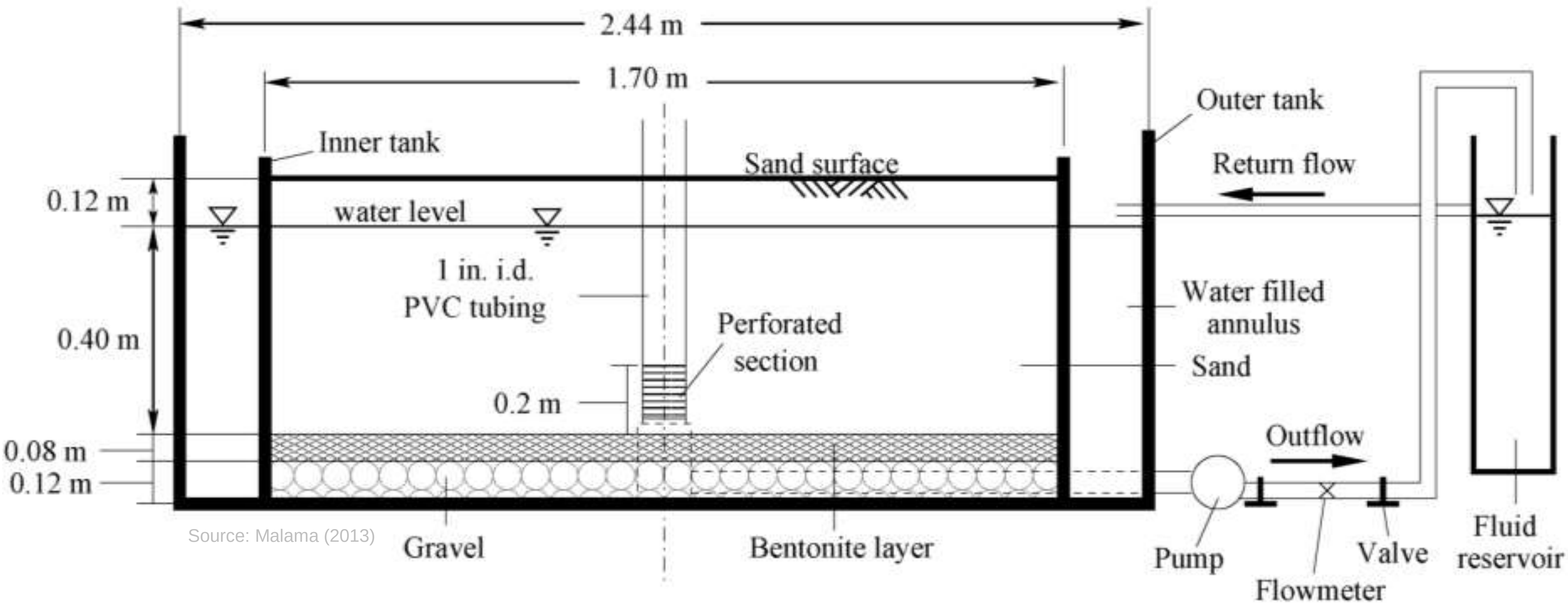
- Malama & Revil (2013) developed a simplified SP solution
  - Estimates flow/electrical properties
  - Simple double-exponential form
  - Good match to late-time permeameter data
- SP voltage a viable surrogate for pressure data!
  - Cheaper / more robust measurements



Clean quartz sand WIPP sand/silt

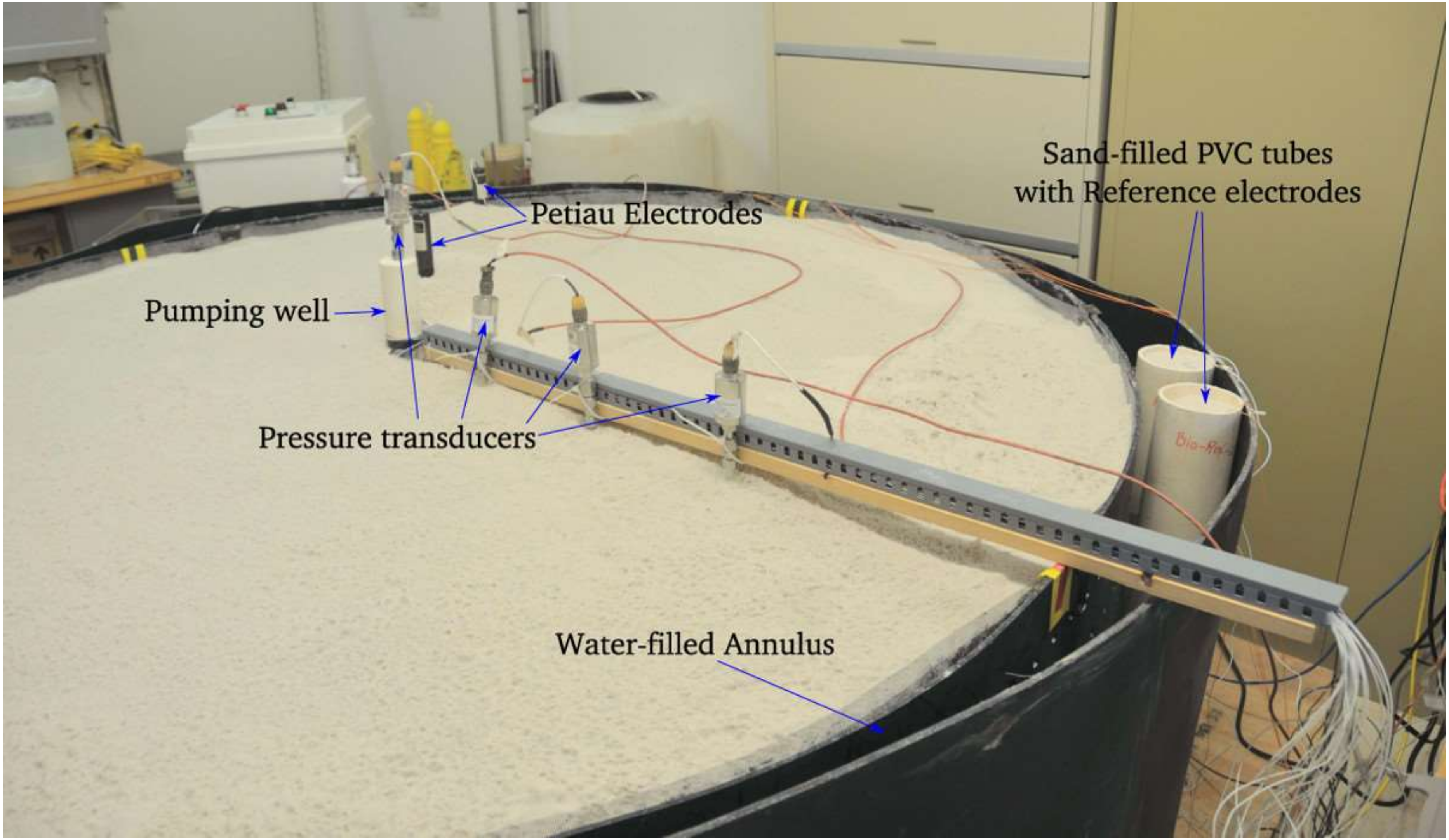
Sandia SP Sand Tank

- Cylindrical sand tank to test theory / methods / electrodes
  - Controlled geometry
  - High instrument density
  - Can change aquifer material



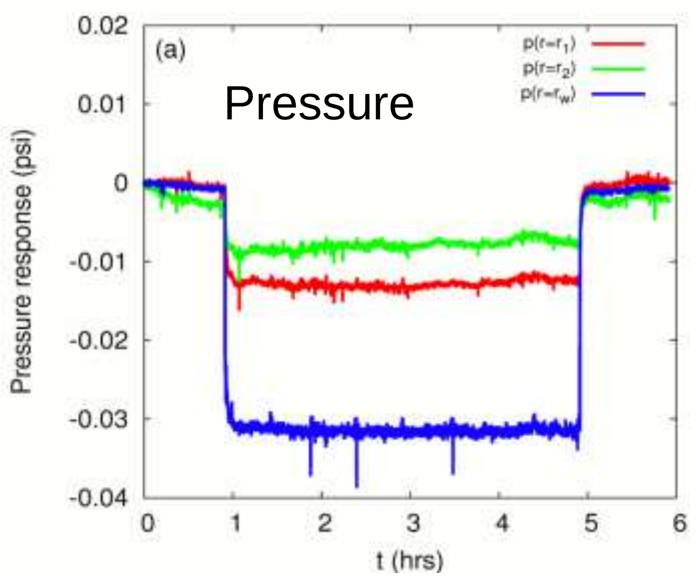
Source: Malama (2013)

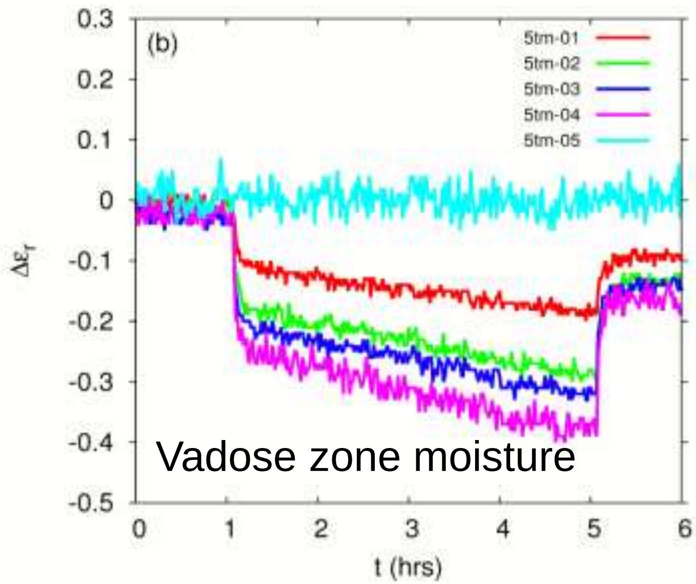
Sandia SP Sand Tank

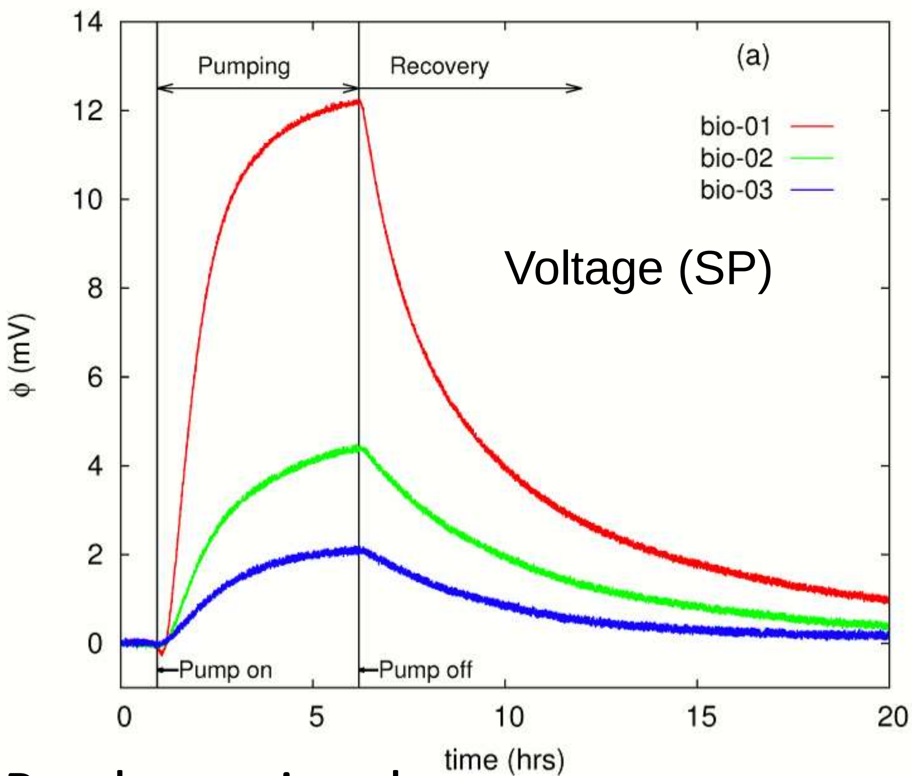


Source: Malama (2013)

SP Lab Test (Carlsbad)







- SP voltage signal
  - Higher signal-to-noise ratio
  - Easier to measure
  - Cheaper sensors
  - Measurable "at a distance"

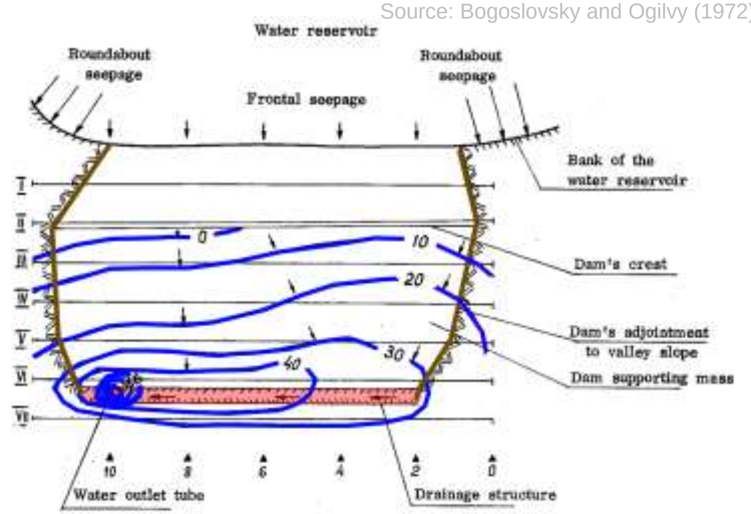
Self-Potential Applications

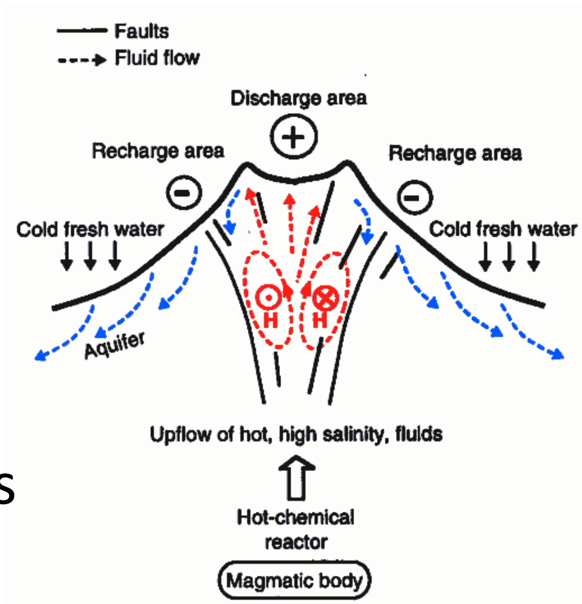
Mostly *qualitative* applications

- Early warning
  - Seepage in dams
  - Seawater intrusion
- Locating focused flow
  - Sinkhole connection mapping
  - Fractured geothermal systems
- Volcano groundwater circulation

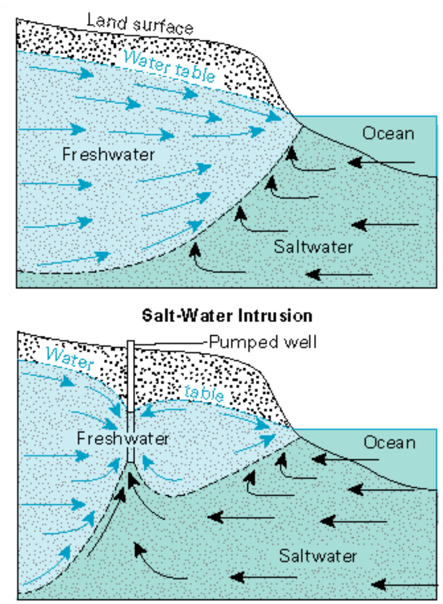
✓ Quantify hydraulic properties during pumping tests

Source: Bogoslovsky and Ogilvy (1972)





Source: Revil, Schwaeger, Cathles & Manhardt (1999)



Source: US Geological Survey

SP Future at Sandia

- Electrode development
- Improving / extending lab instruments
  - Lab sand tank as an SP chemistry test-bed
  - Permeameter for intact cores (low-*Q* / high-*p* systems)
- Possible Sandia collaboration
  - Electrokinetic micropumps (microfluidics 8620)
  - Molecular Dynamics modeling (geochemistry 6915)
  - Electroseismic numerical models (geophysics 6913)
- Sandia advancing hydrogeophysical methods
  - Carlsbad applications through NM Small Business Assistance
  - FY 2015 LDRD Idea

“One man’s noise is another man’s signal”