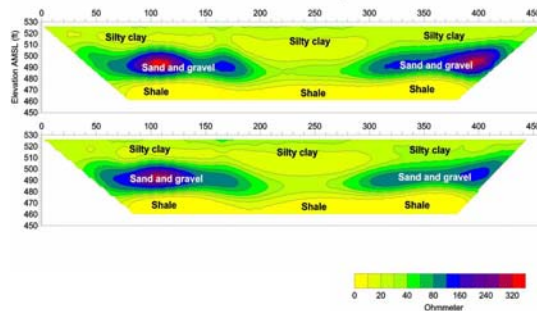
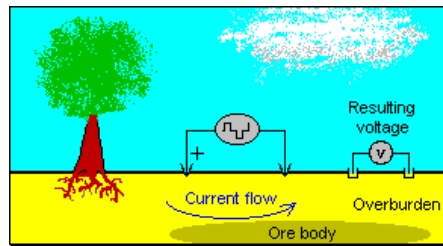


GLE 594: An introduction to applied geophysics

Electrical Resistivity Methods

Fall 2004

Interpretation and Applications



Reading:
Today: 228 - 252

Resistivity Survey

- The aim of resistivity surveys is to delineate vertical and horizontal boundaries with electrical contrasts.
- Two common techniques are used: vertical electrical sounding (vertical boundaries) and electrical profiling (horizontal boundaries)

Vertical Electric Sounding

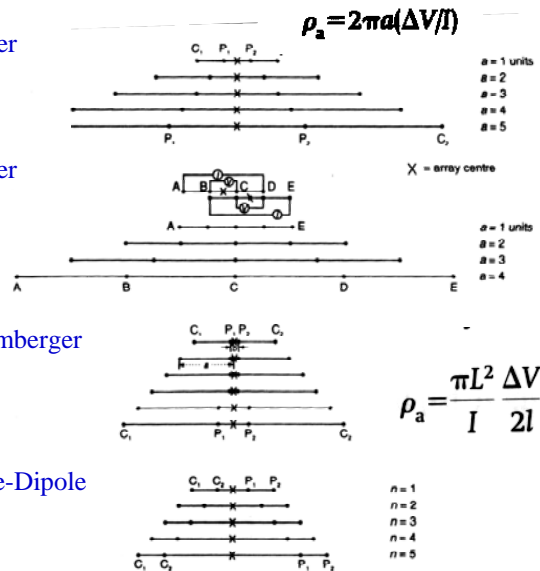
- Different sounding arrangements for different arrays.
- For Schlumberger and Wenner, usually expand electrode separations logarithmically.

Wenner

Offset Wenner

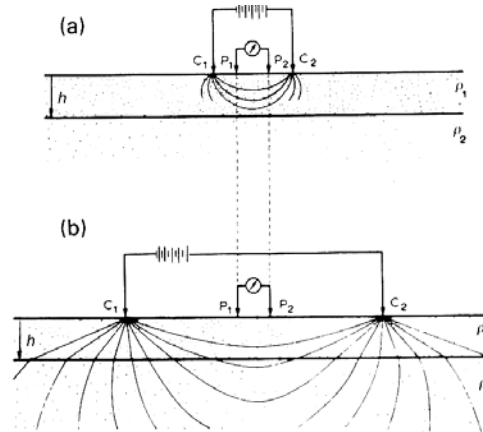
Schlumberger

Dipole-Dipole



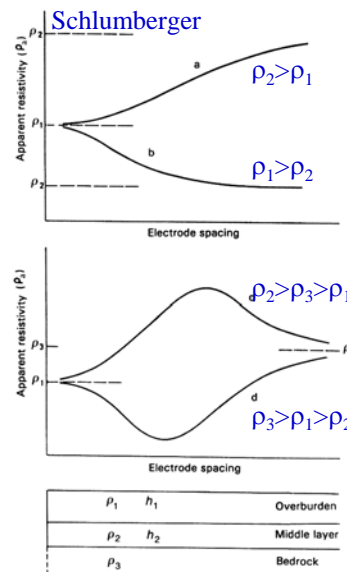
Vertical Electric Sounding

- When trying to probe how resistivity changes with depth, need multiple measurements that each give a different depth sensitivity.
- This is accomplished through *resistivity sounding* where greater electrode separation gives greater depth sensitivity.



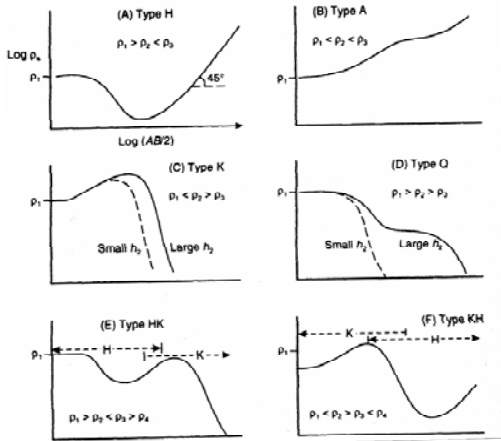
VES Data Plotting Convention

- Plot apparent resistivity as a function of the log of some measure of electrode separation.
 - Wenner – *a* spacing
 - Schlumberger – $AB/2$
 - Dipole-Dipole – *n* spacing
- Asymptotes:
 - Short spacing $\ll h_1$, $\rho_a \approx \rho_1$.
 - Long spacing \gg total thickness of overlying layers, $\rho_a \approx \rho_n$
- To get $\rho_a = \rho_{true}$ for intermediate layers, layer must be thick relative to depth.

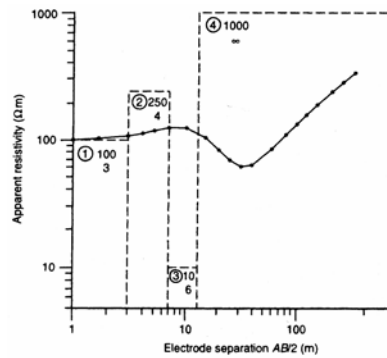


Vertical Electric Sounding

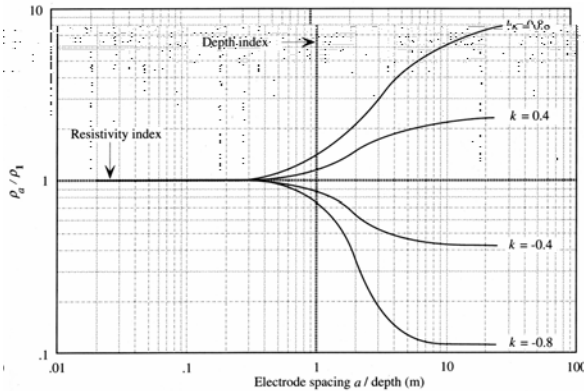
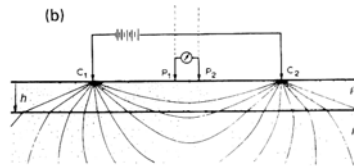
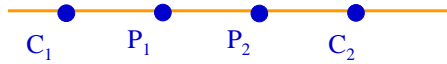
Type curves



Curve vs. resistivity structure



Solutions for a Wenner Array for two layers



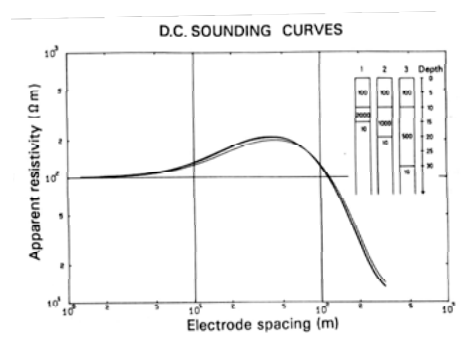
Make ~6 measurements per decade (order of magnitude)

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

Equivalence: several models produce the same results

- Ambiguity in physics of 1D interpretation such that different layered models basically yield the same response.
- Different Scenarios:
 - Conductive layers between two resistors, where lateral conductance (σ_h) is the same.
 - Resistive layer between two conductors with same transverse resistance (ρ_h).

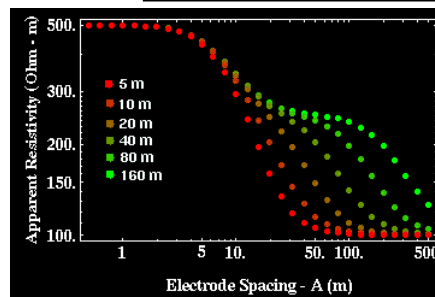
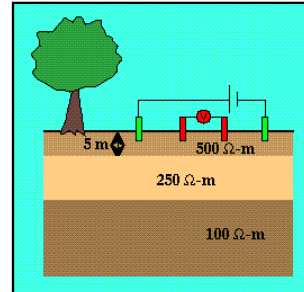
Equivalence: several models produce the same results



- Although ER cannot determine unique parameters, can determine range of values.
- Also exists in 2D and 3D, but much more difficult to quantify. In these multidimensional cases simply referred to as *non-uniqueness*.

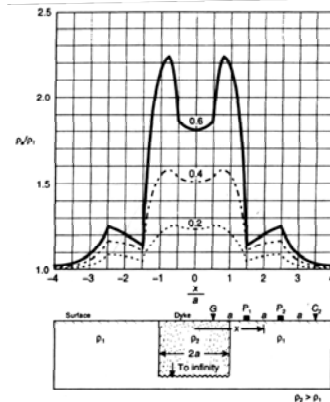
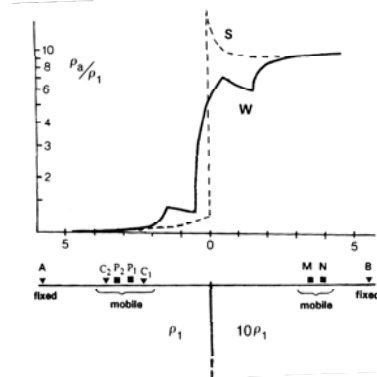
Suppression

- Principle of *suppression*: Thin layers of small resistivity contrast with respect to background will be missed.
- Thin layers of greater resistivity contrast will be detectable, but equivalence limits resolution of boundary depths, etc.



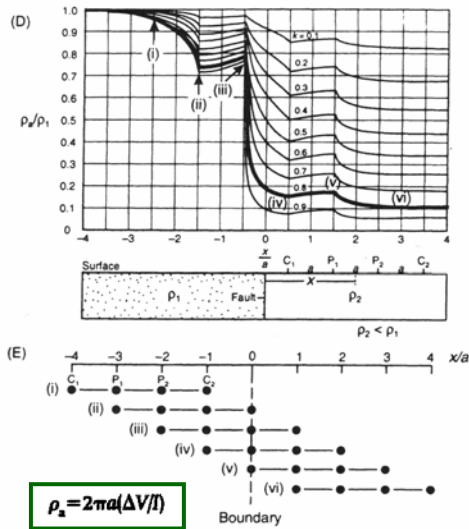
Horizontal Profiling

- Used for rapid location/delineation of lateral variations in resistivity.
- Usually involves moving an electrode array of constant separation horizontally along surface.



- Can be difficult to interpret directly from resulting curve due to formation of 'cusps'. Also, different arrays produce somewhat different results.

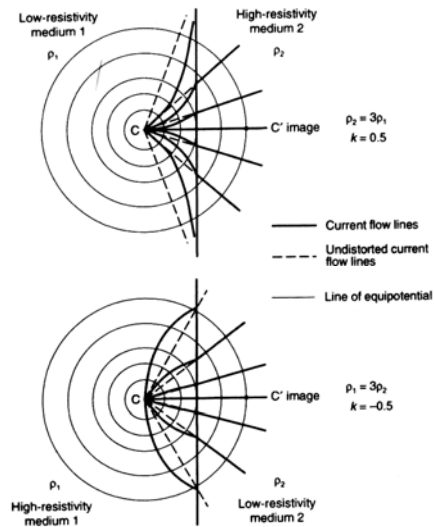
Profile Cusps – Wenner Array



- i. Current lines converge toward boundary, decrease potential gradient at potential electrodes
- ii. C_2 at boundary
- iii. Current density increases adjacent to boundary in low resistivity unit, causes potential gradient between potential electrodes to rise
- iv. Both potential electrodes are in the low resistivity unit so potential gradient between them falls dramatically
- v. C_1 enters the low resistivity unit
- vi. Current flow becomes dipolar

Profile Cusps

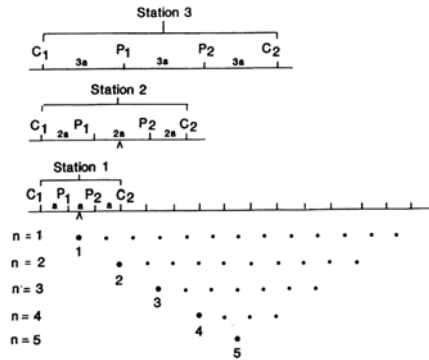
Auxiliary information:



Combined Sounding and Profiling

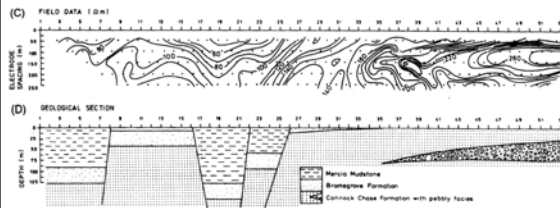
- Increase electrode separation as well as make measurements at multiple locations along the horizontal axis.
- Provides data for two dimensional interpretation of subsurface.
- Data often plotted in *pseudo-section* for qualitative analysis.

Wenner Pseudo-Section

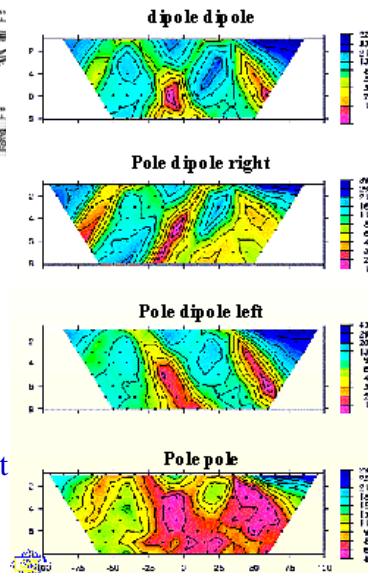


Wenner: $h=a/2$
 Schlumberger: $h=L/3$
 Dipole Dipole: $h=n a$

Pseudo-Sections



- Can sometimes be used to qualitatively assess geology
- Warning: Can also prove to be very difficult to interpret directly, with different arrays yielding very different results.



Pro's and Con's of Different Arrays

Table 6.1 Factors affecting selection of resistivity and IP electrode arrays.

Rating of arrays is from A to E where A is the most preferred and E the least desired array. B, C, D indicate intermediate evaluations in order of preference. Ratings with respect to resolution of structures and sensitivity to surface inhomogeneities are based on specific studies conducted by Coggon (1973), Dey et al. (1975), and Van Zijl (1985).

Array	Signal response	Resolution of horizontal structures	Resolution of steeply dipping structures	Sensitivity to surface inhomogeneities		Electromagnetic coupling noise (IP)
				(sounding)	(profiling)	
Wenner	A	A	C	B	C	E
Schlumberger	B	A	B	A	C	D
Gradient	C	E	A	E	F	C
Pole-dipole	D	B	E	C	A	B
Dipole-dipole	E	B	D	D	B	A

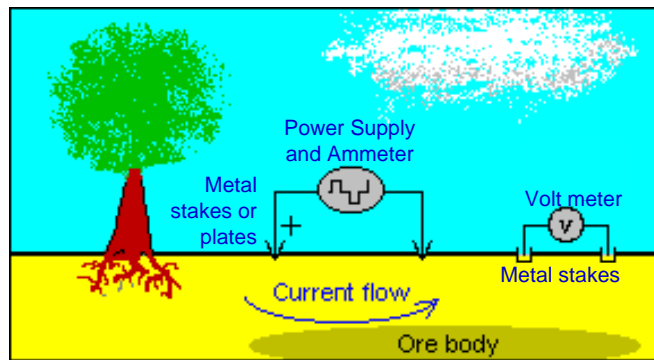
Measurement Systems

Transmitter

- Power Supply
 - DC
 - AC (more common)
- Ammeter
- Metal electrodes

Receiver

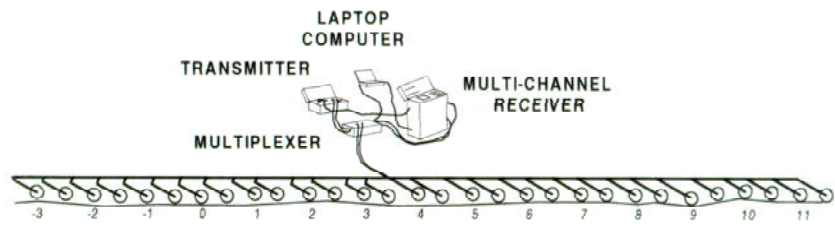
- Voltmeter
- Metal Electrodes



Fully Automated Systems

Zeta Setup

30 Electrode Spread Shown



Electrodes: 30
Station Spacing: 1/2 Dipole
N-spacings: 12 per diagonal ($n=0.5, 1, 1.5, 2, \dots$)
Data points per Spread: 234

Field Considerations for DC Resistivity

- Good electrode contact with the earth
 - Wet electrode location
 - Add NaCl solution or bentonite.
- Surveys should be conducted along a straight line whenever possible
- Try to stay away from cultural features whenever possible (power lines, pipes, grounded metal fences, pumps, etc)

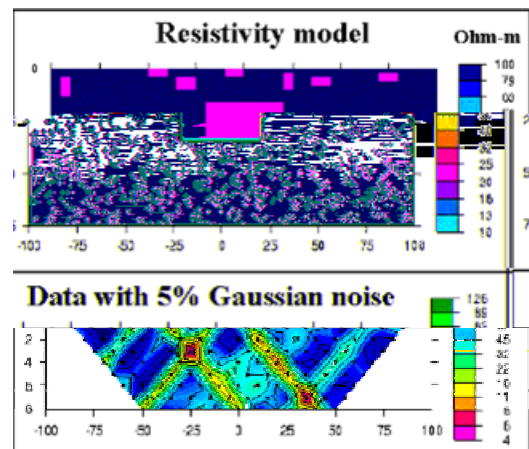


Sources of Noise in Data

- Instrument noise
- Cultural Features
- Telluric Currents – naturally occurring earth currents.
 - Self potentials – generally caused by either geochemical reactions or greater than normal subsurface fluid flow.
 - Magnetotelluric Currents – Electromagnetically induced by naturally occurring or man-made magnetic fields.
 - In some cases, it may be unavoidable

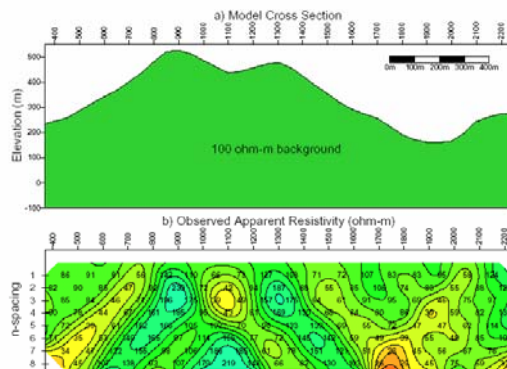
Sources of Noise in Data

- Geologic Noise
 - Near surface variations: Can dominate response thus masking signature of deeper targets.



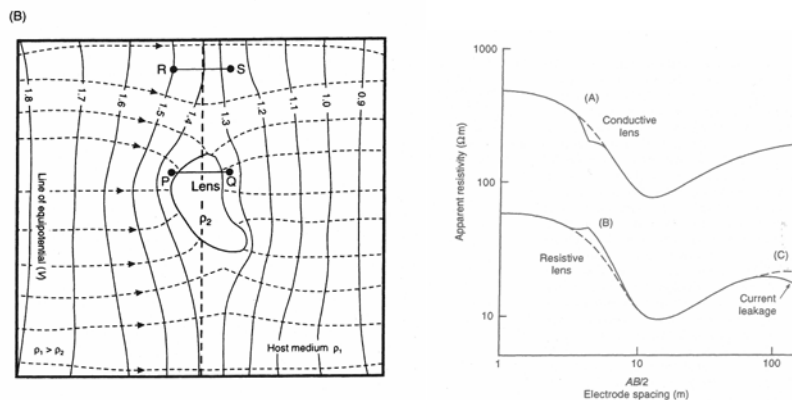
Sources of Noise in Data

- Geologic Noise
 - Topography: Currents will be *focused* under valleys, and *dispersed* under hills, thus causing perturbations in measured voltages.



Sources of Noise in Data

- Small heterogeneities produce cusps
- Long linear features (rivers, wires) may produce current leakage.

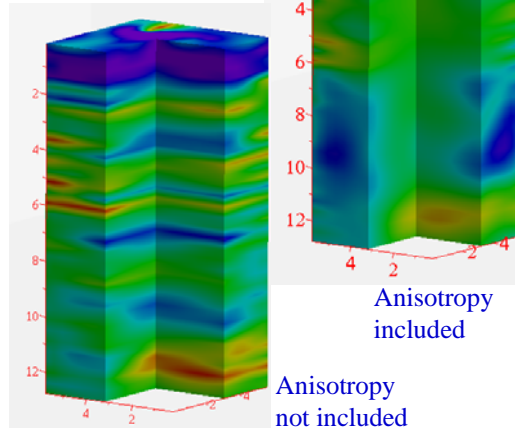


Sources of Noise in Data

Geologic Noise

- Electrical anisotropy: Different resistivity if measured parallel to the bedding plane compared to perpendicular to it. Examples:
 - Clays – Mineral *platelets* preferentially aligned such that current wants to flow parallel to plates.
 - Thin bedding planes
 - Unsaturated zone – in areas of alternating grain size distribution (fluvial deposits) will get alternating series of high and low moisture contents.

Transverse isotropy will result in a compressed vertical scale.



Generalized Profile Interpretation

- Looking for changes in apparent resistivity that will enhance your understanding of what you already know about the geology.

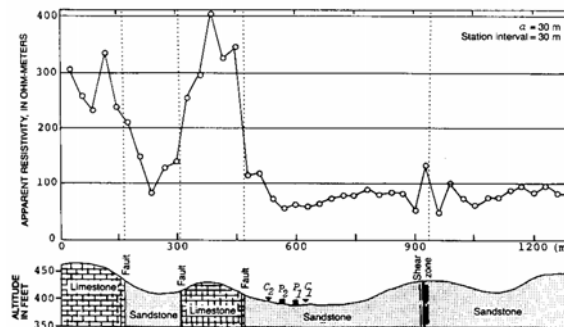
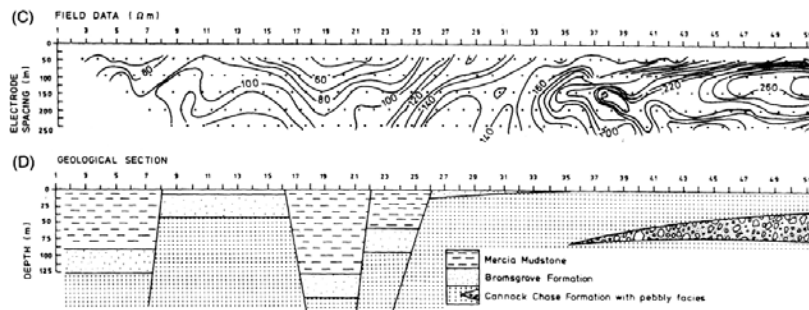


Fig. 6.19 Horizontal resistivity profile across a shear zone and limestone fault block in Illinois; Wenner configuration. (After Hubbert, 1932.)

Qualitative 2D Profile Interpretation

- Sometimes pseudo-sections can be interpreted qualitatively directly if
 - Good data quality
 - Simplified geology
- This is the exception rather than the norm



Quantitative 1D Analysis – Master Curves

- Simple for two layer case.
 - Plot data at same scales as master curves.
 - Overlie shallow-layer resistivity asymptote with '1' on master curves.
 - Determine depth to layer, and resistivity of lower layer by comparing scaled master-curve values to data values
- Gets rapidly more difficult as more layers added.

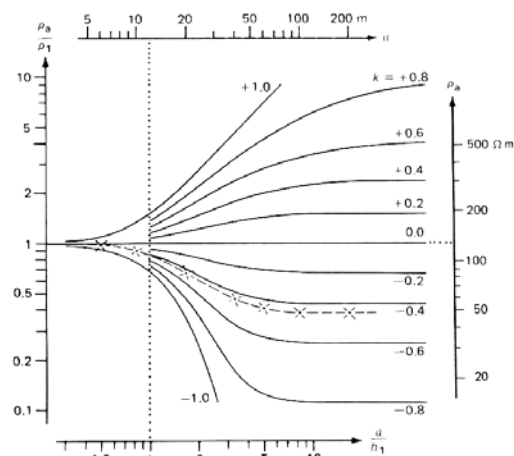
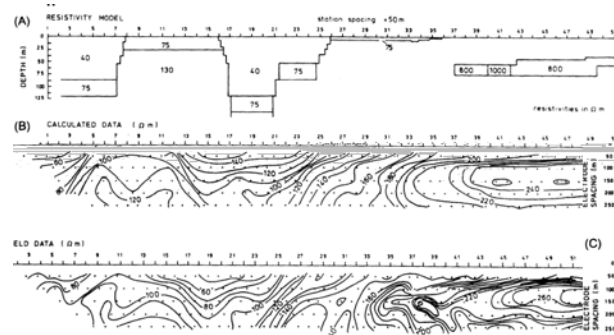


Fig. 6.16 Example of the interpretation of a field curve (dashed line with crosses) by matching it with a set of master two-layer resistivity curves (for explanation see text).

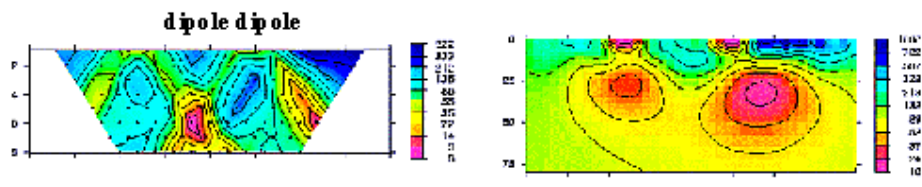
Computerized Interpretation: Forward Modeling

- Using mathematical expressions that describe the physics to calculate the data that would result from a given combination of geoelectric model and electrode configuration.
- Generally a *linear* process.
- Forward modeling produces *unique* results.



Computerized Interpretation: Inverse Modeling

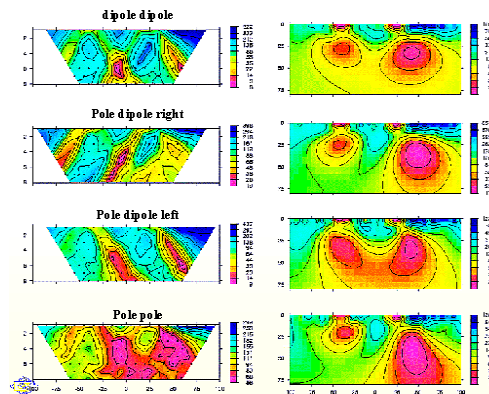
- Going the opposite direction. We measure data and know the array configuration, and through *inversion* wish to determine a geoelectric model that would produce data similar to those measured.
- Problems:
 - Generally problem is non-linear.
 - Problem is non-unique. Thus must add constraints of some sort to provide a reasonable answer.
 - Danger in over-interpreting the results.



Inverse Modeling

- Benefits:

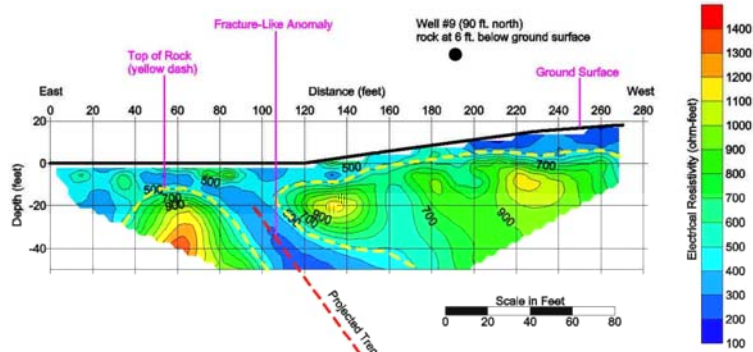
- Automatic, it helps to remove *user bias*. *However sometimes the user's bias is needed to produce a decent model*
- Automatically removes differences associated with different electrode collection schemes.



Interpretation Issues - Resolution

- General 2D and 3D surveys
 - Basically, spatial resolution falls off as you get further away from the surface. Need larger bodies/higher contrasts at greater depths to be detectable
 - Near surface very well resolved – min. horizontal resolution equal to minimum electrode separation
 - Depth resolution is array dependent
 - REMEMBER – Over-interpretation is very easy given the non-uniqueness of physics as well as the inverse problem. Thus need to be careful.

Locating Water Bearing Fracture Zones in Bedrock



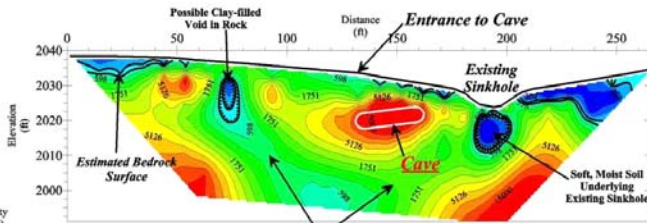
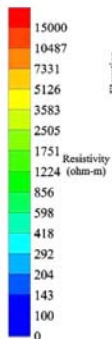
Objective: To locate a water well in red shales and siltstones of the Triassic Brunswick Formation.
 Location: Bucks Co., PA
 Survey date: August 1999
 Processing: Res2Dinv software, inversion RMS error 3.6%
 Electrode array: Dipole-dipole
 Equipment: Sting/Swift resistivity meter using 30 electrodes at 3 meter spacing.

Well #9 Reports Water-Bearing Zone from 145 to 150 ft. (approx. 100 gpm)

Courtesy of Quantum Geophysics, Inc., Phoenixville, Pennsylvania

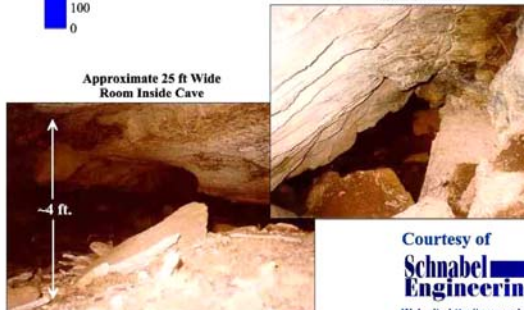
AGI Advanced Geosciences, Inc.
 Tel: +1 (512) 335-3338
 Fax: +1 (512) 258-9958
 E-mail: sales@agiusa.com
 Web site: http://www.agiusa.com

Legend



Scale
 Horizontal: 1" = 40'
 Vertical: 1" = 25'

Looking into Cave from Entrance



Approximate 25 ft Wide Room Inside Cave



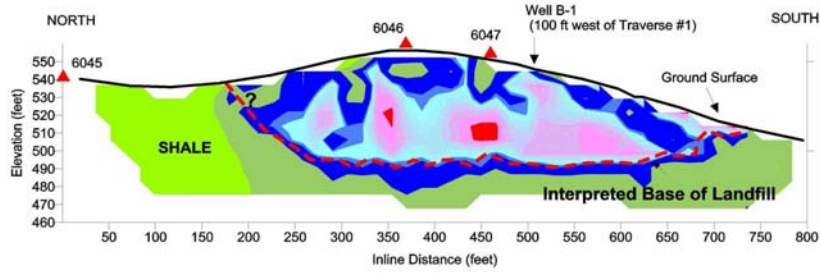
Cave Entrance

The above two-dimensional resistivity profile was conducted over top of the cave shown. Data was recorded using the Sting/Swift automatic system with 28 electrodes at 2 m spacing in a dipole-dipole array. Soil coverage was thin, rock was within 6 inches of the ground surface above the cave. Adjacent to the cave entrance was an existing sinkhole. Both the cave and fractures beneath the sinkhole can be seen in the profile.

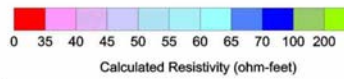
Courtesy of
Schnabel Engineering

AGI Advanced Geosciences, Inc.
 Tel: +1 (512) 335-3338
 Fax: +1 (512) 258-9958
 E-mail: sales@agiusa.com
 Web site: http://www.agiusa.com

Mapping the Limits of a Municipal Landfill



▲ Bore hole

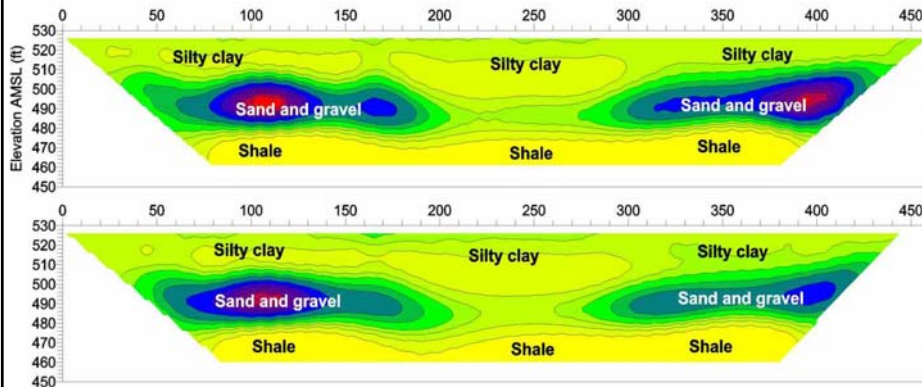


Objective: To map the horizontal and vertical extent of a landfill
 Instrument: Sting/Swift automatic resistivity imaging system, with 56 electrodes at 6 meter spacing
 Method: Dipole-dipole electrode array
 Processing: Inversion and topographic correction using the Res2Dinv software
 Units: Feet and ohmfeet

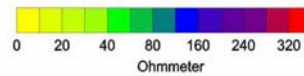
Courtesy of
SAIC
 An Employee-Owned Company
 GEOPHYSICAL SERVICES
 Middletown, Pennsylvania

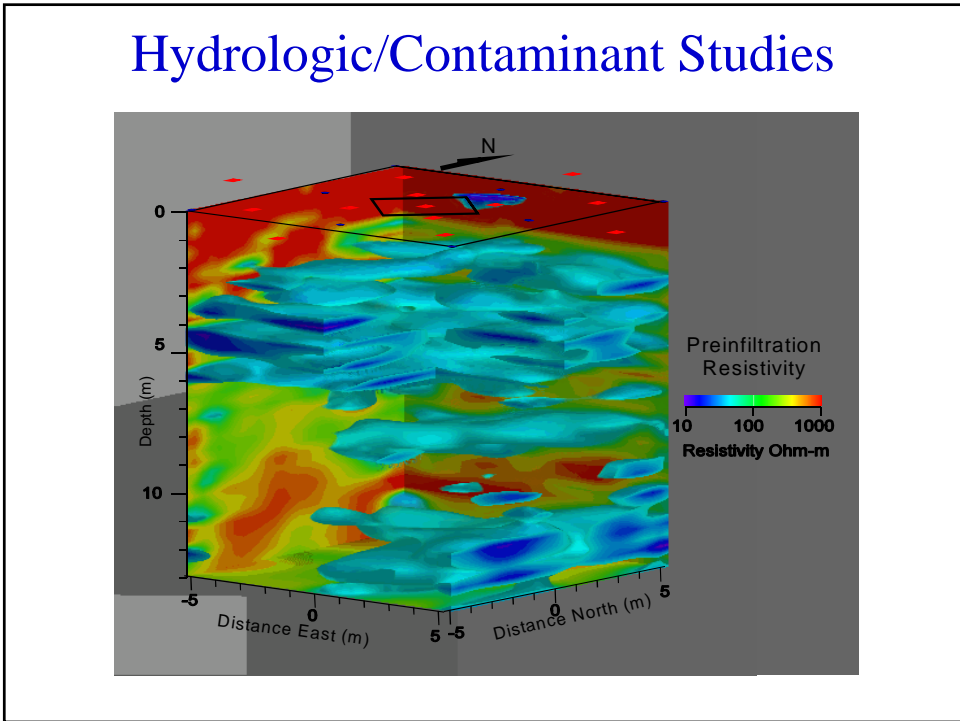
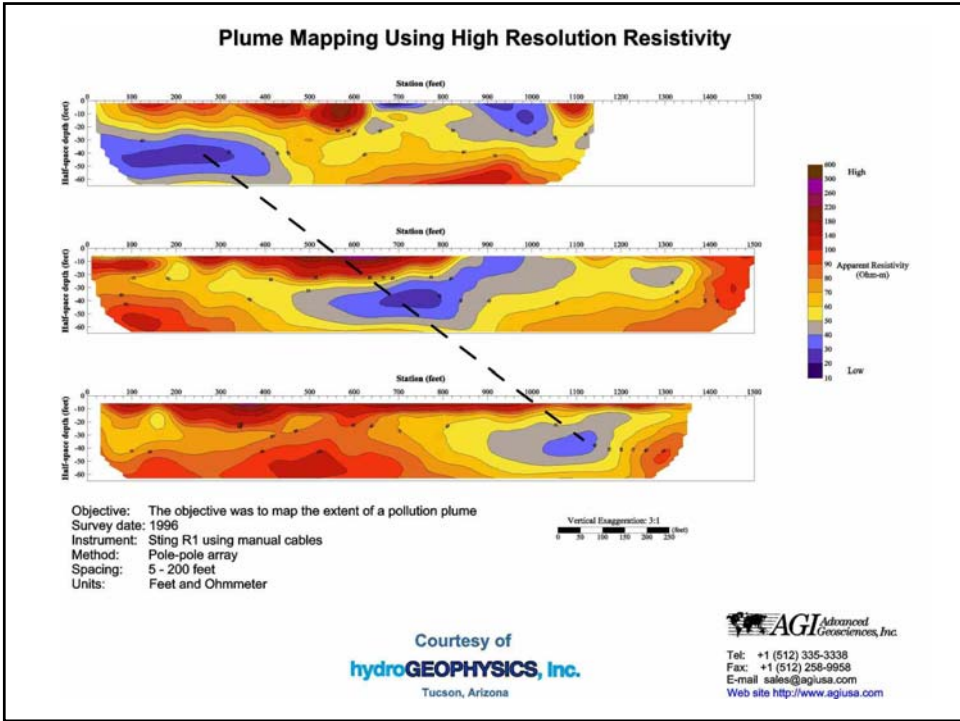
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 Fax: +1 (512) 258-9958
 E-mail: sales@agiusa.com
 Web site: <http://www.agiusa.com>

Mapping of Stratigraphy Sand and Gravel Lenses in Clay Environment



Two parallel profiles, 25' apart. Sand and gravel solution channels show higher resistivity than the silty clay or the shale. Note how the two profiles show almost the same layering since they are only 25' (ca 8 m) apart.



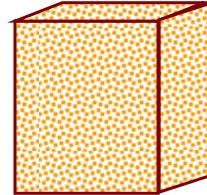


Archie's Law

- Empirical relationship defining bulk resistivity of a saturated porous rock:

$$\rho_0 = a\rho_w\phi^{-m}$$

- ρ_0 = bulk rock resistivity
- ρ_w = pore-water resistivity
- a = empirical constant ($0.6 < a < 1$)
- m = cementation factor (1.3 poor, unconsolidated) $< m < 2.2$ (good, cemented or crystalline)
- ϕ = fractional porosity (vol liq. / vol rock)



Archie's Law (continued)

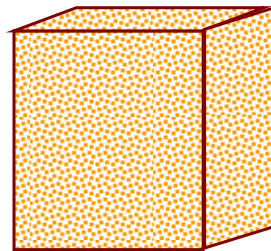
- Formation Factor:

$$F = \frac{\rho_0}{\rho_w} = a\phi^{-m}$$

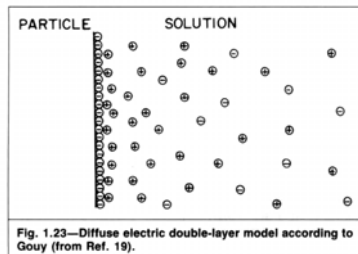
- Effects of Partial Saturation:

$$\rho_t = S_w^{-n} a\rho_w\phi^{-m}$$

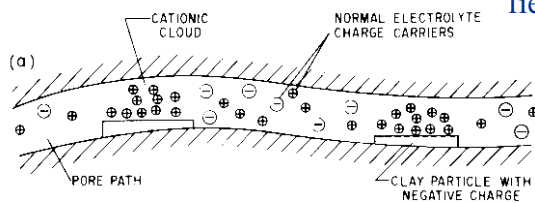
- S_w is the volumetric saturation.
- n is the saturation coefficient ($1.5 < n < 2.5$).



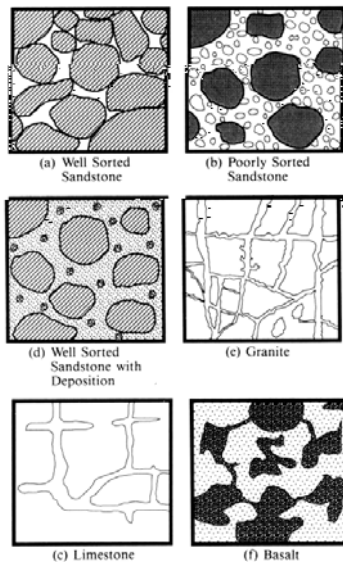
Effects of Clay Minerals



- Net negative charge of clay causes formation of a double layer of cations.
 - Fixed layer of cations immediately adjacent to clay particle.
 - Diffuse layer further out. Not strongly bound and thus free to move in an applied electric field.



Rock *Texture* and Resistivity



Change in Resistivity

Clay Alteration	↕	Weathering	↕
Dissolution	↕	Induration	↑
Faulting	↕	Carbonate Precipitation	↑
Salt Water Intrusion	↕	Silicification	↑
Shearing	↕	Metamorphism	↕
↕ Decreases ↑ Increases ↕ Increases or Decreases			