Hydrology

Jürg M. Matter

Lamont-Doherty Earth Observatory, The Earth Institute at Columbia University

May 9, 2008

jmatter@ldeo.columbia.edu

Outline

- Background
- Flowmeter Logging – Fluid Movement Logging
- Fluid Logging (temperature, fluid resistivity)
- Borehole Televiewer Logging – Television camera
- Case Study LDEO Testwells

jmatter@ldeo.columbia.edu

Borehole Geophysics in Groundwater Studies

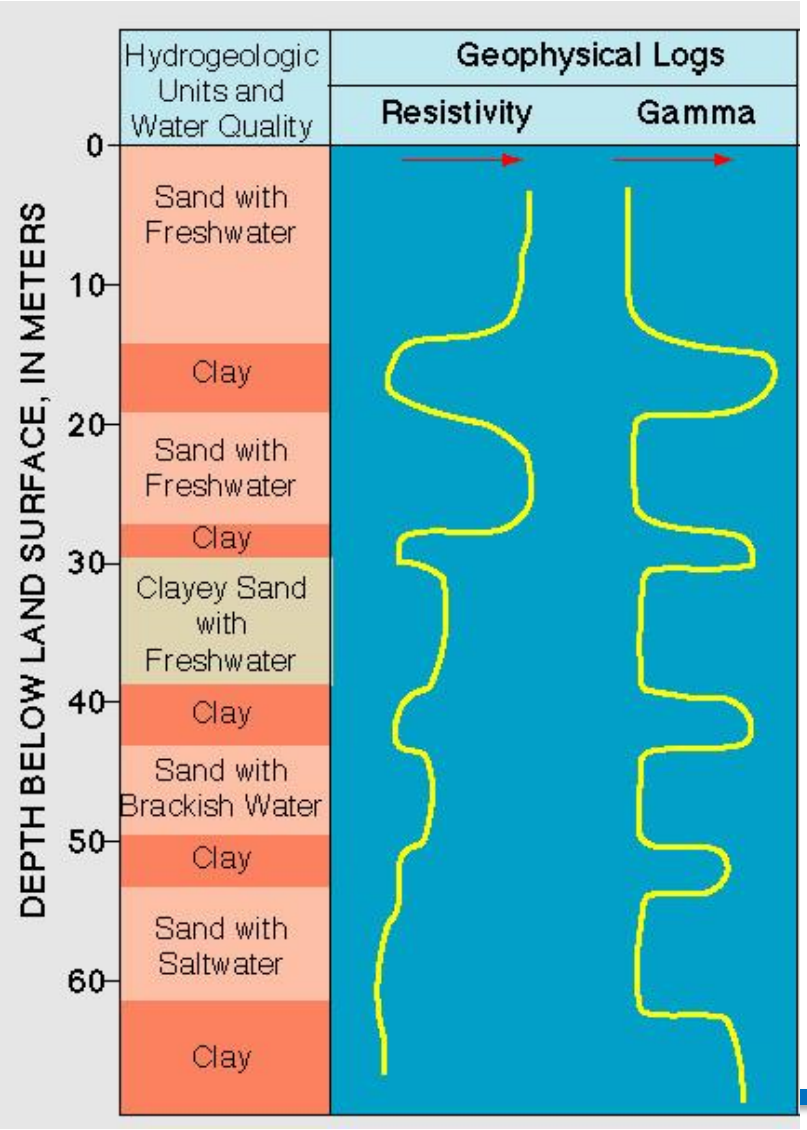
- 1890's first geophysical well logs plotted from temperature measurements made by W. B. Hallock (1897)
- C. E. Van Orstrand (1918) USGS, described downhole-temperature equipment with a sensitivity of 0.01°C
- Orstrand thought that temperature curves could be used to determine relative water content of rocks in situ
- Well logs can be used to determine lithology, porosity, density, moisture content, clay content, direction and velocity of flow, water level, water conductive fractures
- **No direct determination of permeability by logging**

jmatter@ldeo.columbia.edu

Equipment

jmatter@ldeo.columbia.edu

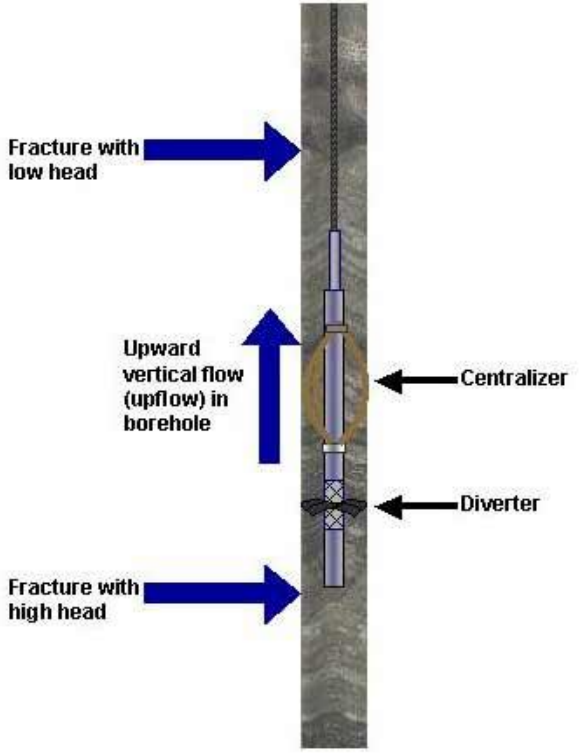
Hydrostratigraphy



jmatter@ldeo.columbia.edu

Flowmeter Logging

- conventional single hole flowmeter logging – ambient, pumping or injection conditions
- vertical or horizontal flow logging
- cross-hole flowmeter logging – pumping or injection conditions
- discrete interval hydraulic testing – pumping or injection conditions
- discrete interval sampling



http://water.usgs.gov/ogw/bgas/flowmeter/

jmatter@ldeo.columbia.edu

Flowmeter Tools

1. Heat-pulse Flowmeter

- Measurement at stationary position
- Activation of heat grid to heat packet of water
- Movement of heated water packet if flow in well
- Monitoring difference in T between sensors
- Measurement of time difference between activation and greatest T measurement
- Calculation of rate of flow and direction
- resolution 0.01 to 1.5 gallons/min

http://water.usgs.gov/ogw/bgas/flowmeter/

jmatter@ldeo.columbia.edu

2. Electromagnetic Flowmeter

- based on Faraday's law of induction
- electromagnet generates a magnetic field in hollow cylinder within the tool
- flow of water (conductor) thorough magnetic field at 90° to the field induces a voltage
- voltage measured by electrodes within the tool and used to calculate velocity of water through fixed-diameter chamber
- flow velocity used to calculate volumetric flow
- measurement while moving or stationary
- resolution 0.5 – 10 gallons/min

http://water.usgs.gov/ogw/bgas/flowmeter/

jmatter@ldeo.columbia.edu

2. Spinner or Impeller Flowmeter

- impeller revolves in response to fluid flow
- recording of number of impeller revolutions per second and used to calculate fluid velocity
- measurement while moving or while stationary
- minimum velocity is ~5 feet/min
- generally poor resolution

http://water.usgs.gov/ogw/bgas/flowmeter/

jmatter@ldeo.columbia.edu

Vertical Flowmeter Logging

Single hole

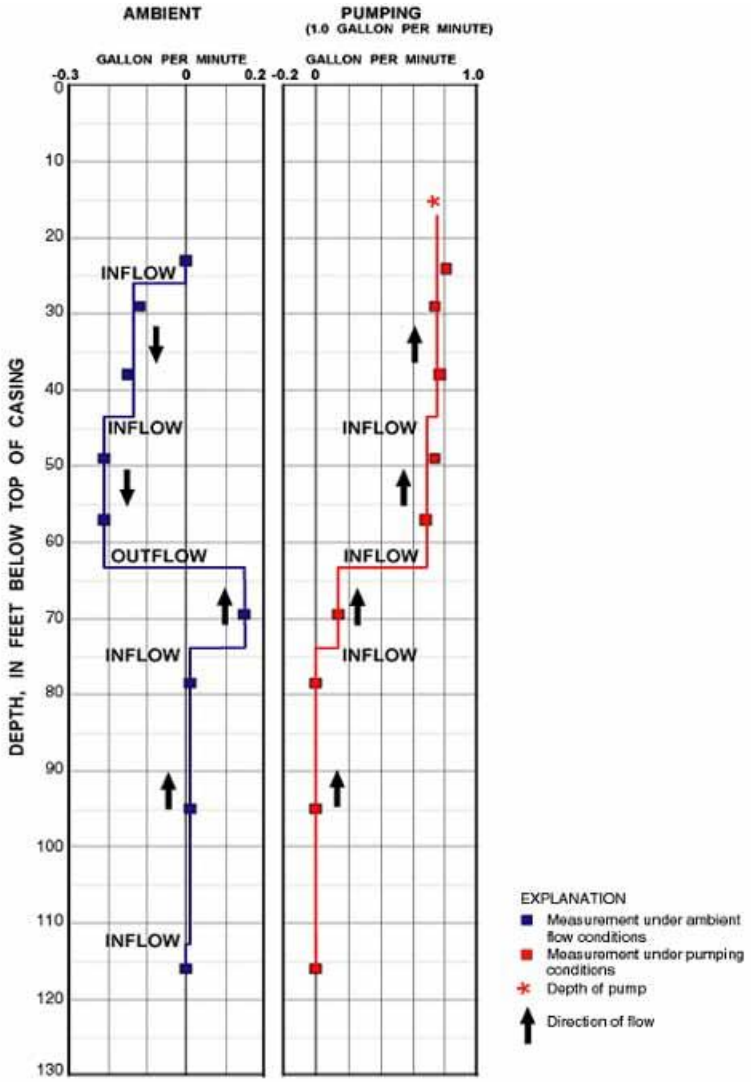
- measurement of vertical movement of fluid in a borehole, produced by difference in hydraulic head between two permeable units
- measurement of rate and direction of vertical flow
- relative hydraulic gradients
- indentify permeable units or fractures

Cross-hole

- identify cross-hole connections
- transmissivity
- hydraulic heads
- storage coefficient of permeable unit or fracture between borehole

jmatter@ldeo.columbia.edu

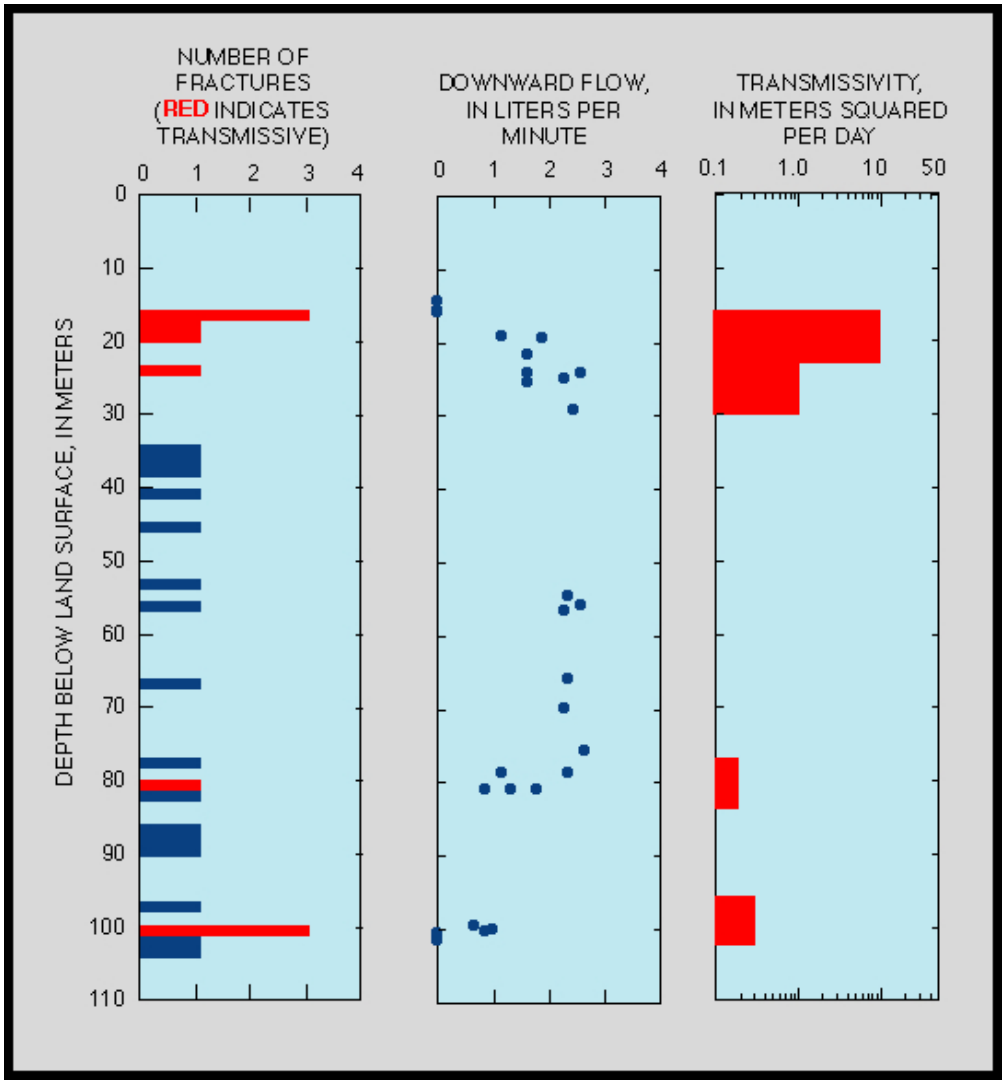
Single Hole Flowmeter Log



- **fluid moves from higher head to lower head!**

http://water.usgs.gov/ogw/bgas/flowmeter/

jmatter@ldeo.columbia.edu

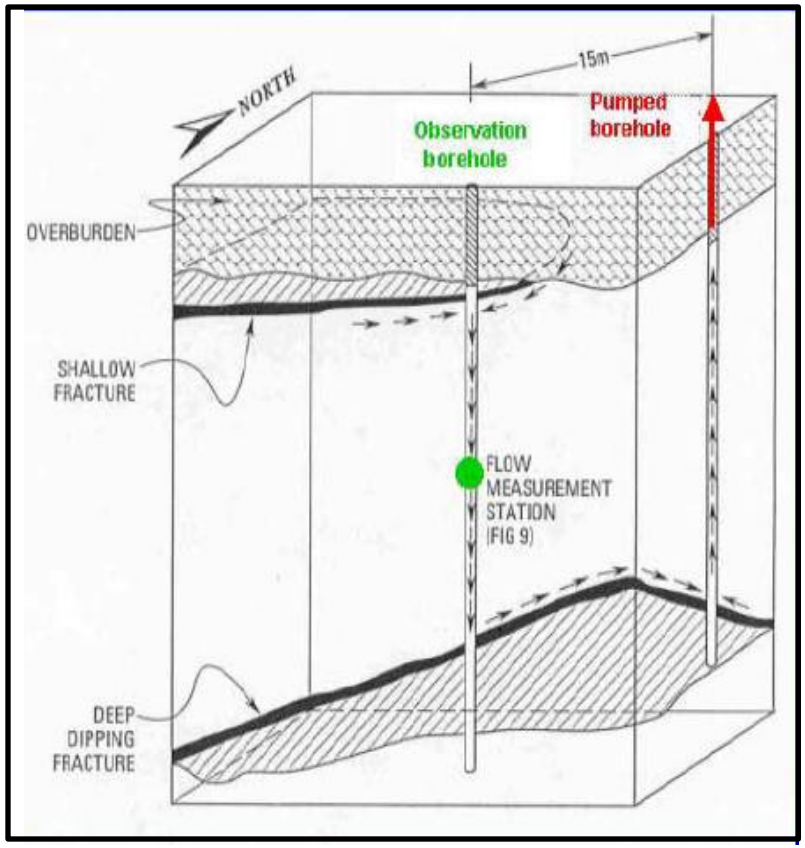


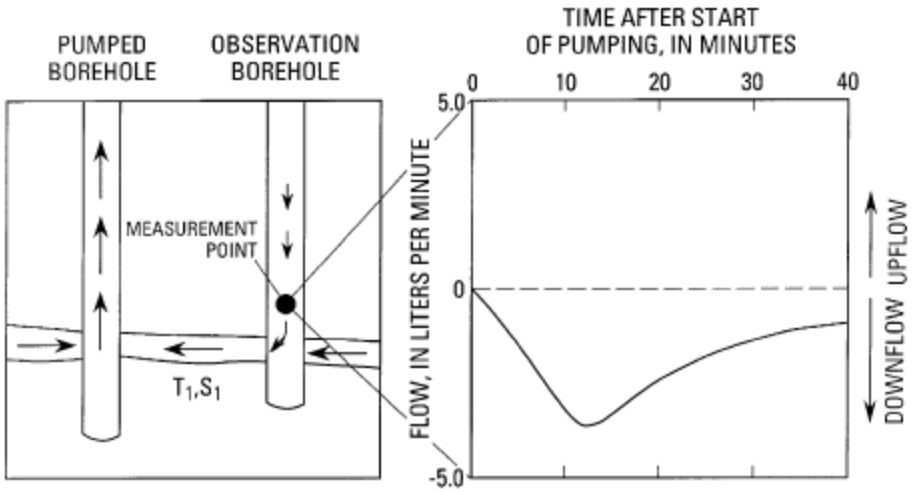
Williams and Conger (1990)

- detection of transmissive zones
- fracture distribution determined by acoustic televiewer
- Transmissivity estimated from pumping tests using straddle packer

jmatter@ldeo.columbia.edu

Cross-Hole Flowmeter Log





Williams and Paillet (1998)

jmatter@ldeo.columbia.edu

Horizontal Flowmeter Logging

- **KVA Heat-Pulse Flowmeter**
- **Scanning Colloidal Borescope Flowmeter (LLNL)**

- evaluates horizontal groundwater flow direction and velocity

- employs a charge couple device, magnetometer, light source and remotely controlled focal lens mechanism to track colloid-sized particle

- **Acoustic Doppler Velocimeter (USGS)**

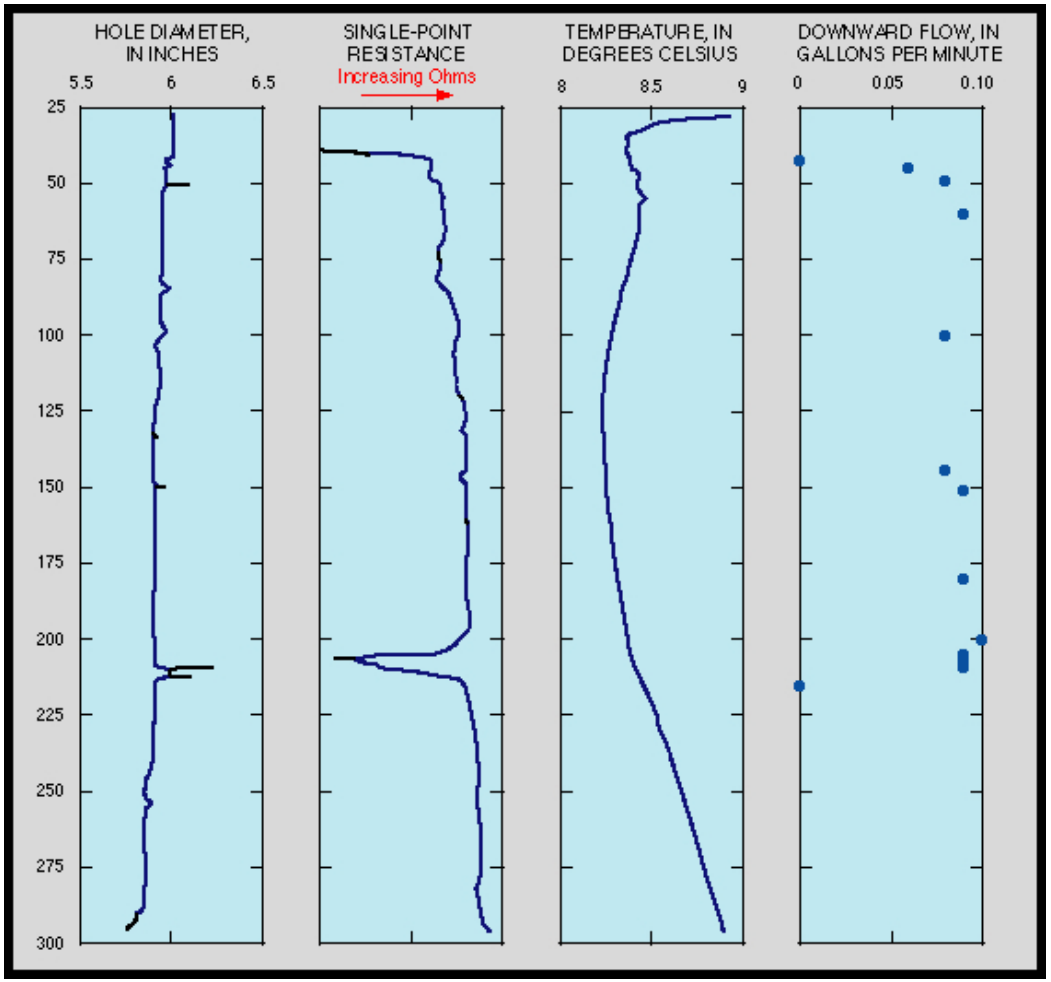
- position of colloids is measured by acoustic reflections

- as colloids move with groundwater, software tracks the particle paths and calculated transport rate and direction

- Built-in magnetometer

jmatter@ldeo.columbia.edu

Fluid Logging - Temperature

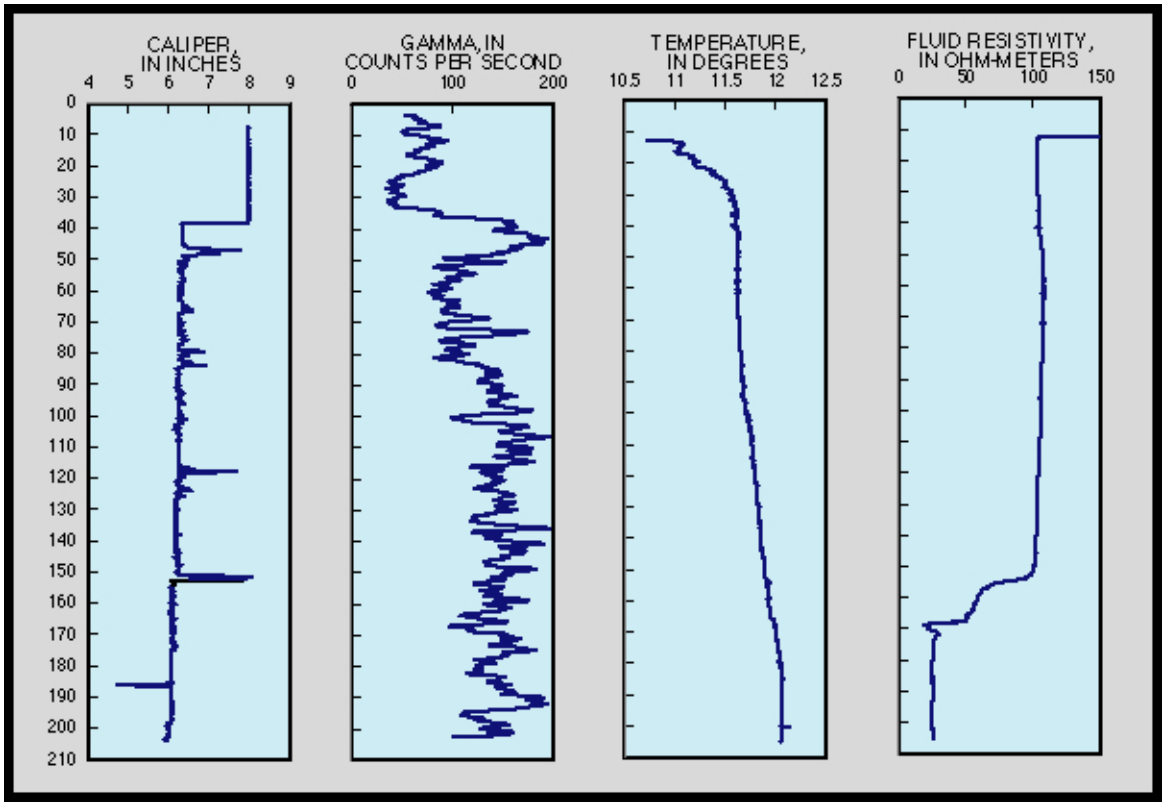


http://ny.water.usgs.gov

- used to delineate water-bearing zones
- identify vertical flow between zones of different hydraulic head
- flow is indicated by T-grad < regional geothermal gradient
- used to identify recharge water and liquid waste discharges to the ground
- convection in well can disturb thermal gradient (deep and large wells)

jmatter@ldeo.columbia.edu

Fluid Logging – Fluid Resistivity (ohm-m)



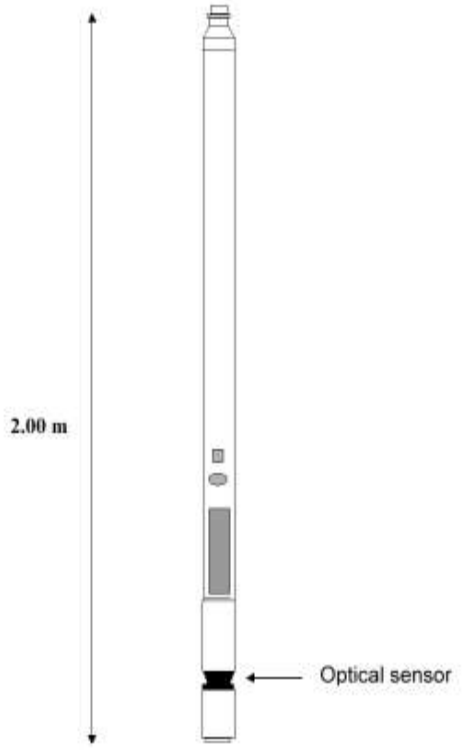
http://ny.water.usgs.gov

- used to identify water-bearing zones, vertical flow, contaminants
- probe measures AC-voltage drop across two closely spaced electrodes -> function of fluid resistivity
- fluid conductivity (mhos/cm) is reciprocal of resistivity (10,000 / resistivity)

jmatter@ldeo.columbia.edu

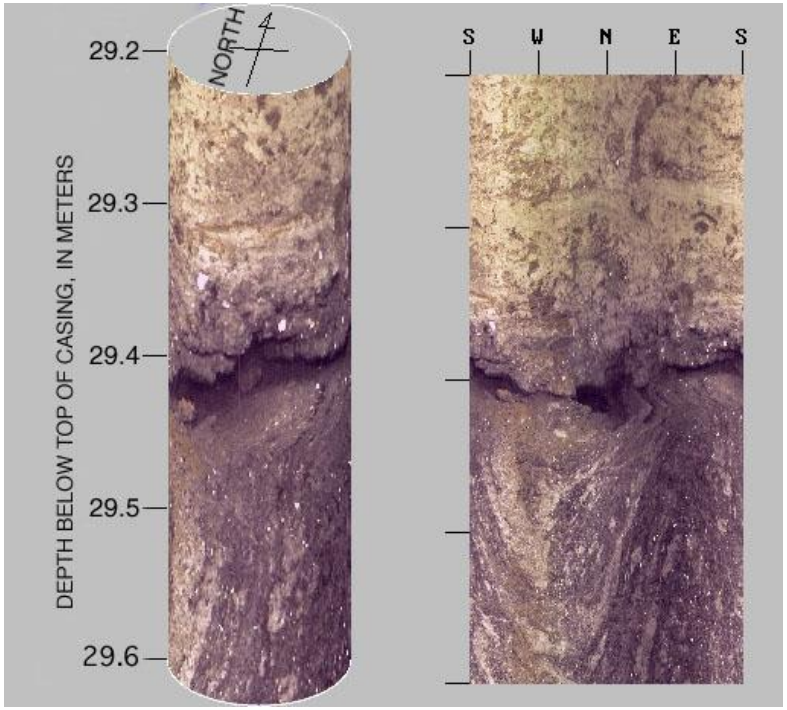
Borehole Televiewer Logging

- used to obtain oriented images from borehole wall
- two different technologies are available: acoustic televiewer, optical televiewer
- acoustic televiewer uses an acoustic signal from a rotating sonar transducer
- optical televiewer uses a high resolution digital color camera with a light source
- both have a built-in magnetometer to orient the image with respect to magnetic north
- identify fractures, breakouts and other borehole features



jmatter@ldeo.columbia.edu

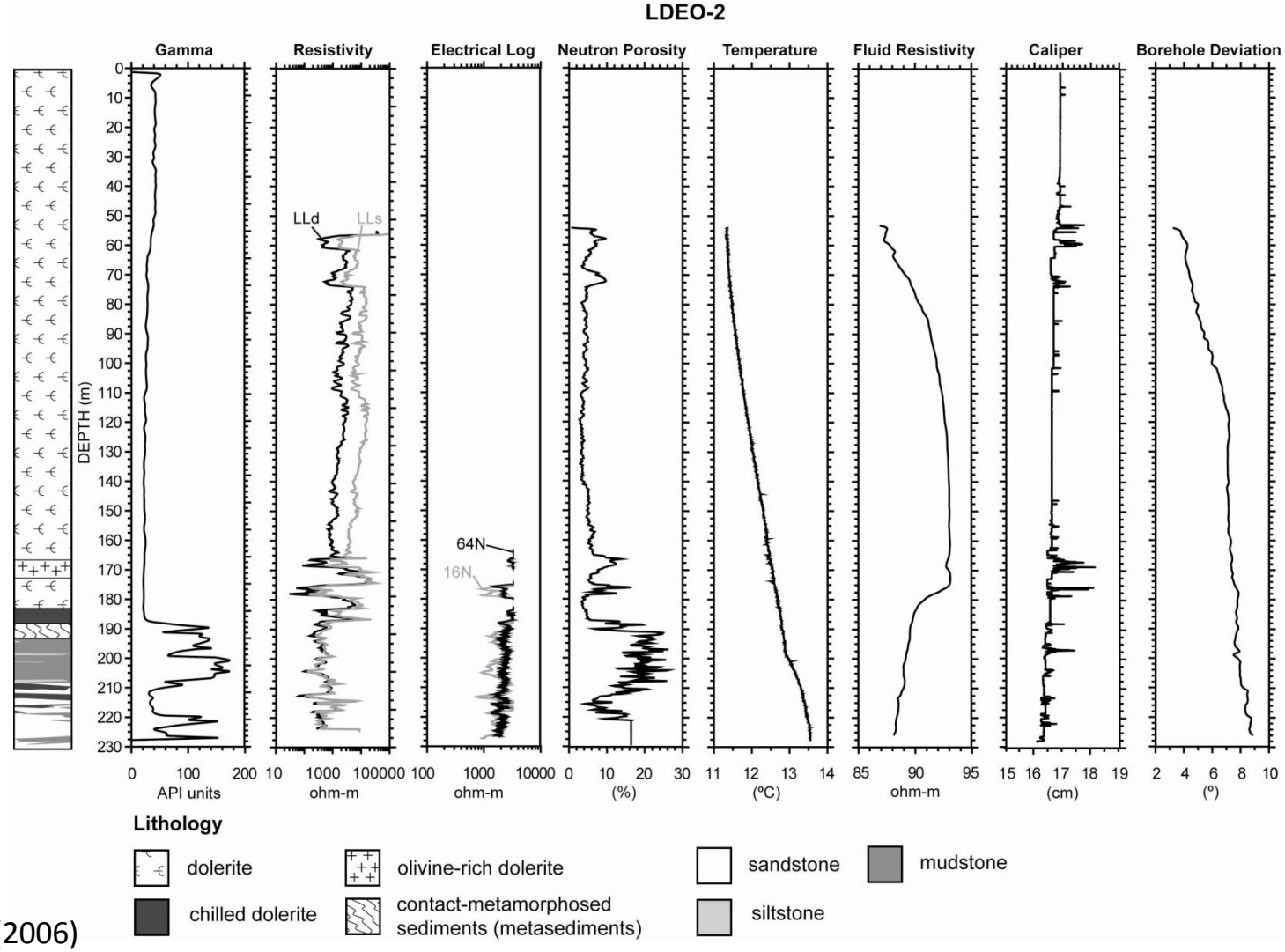
Digital Borehole Television Camera



- commonly used to inspect well casing conditions and screens
- also used to view: lithologic texture, grain size, color, water levels, fractures
- applicable in clear water above and below water level
- built-in magnetometer for oriented 360º digital images of borehole wall

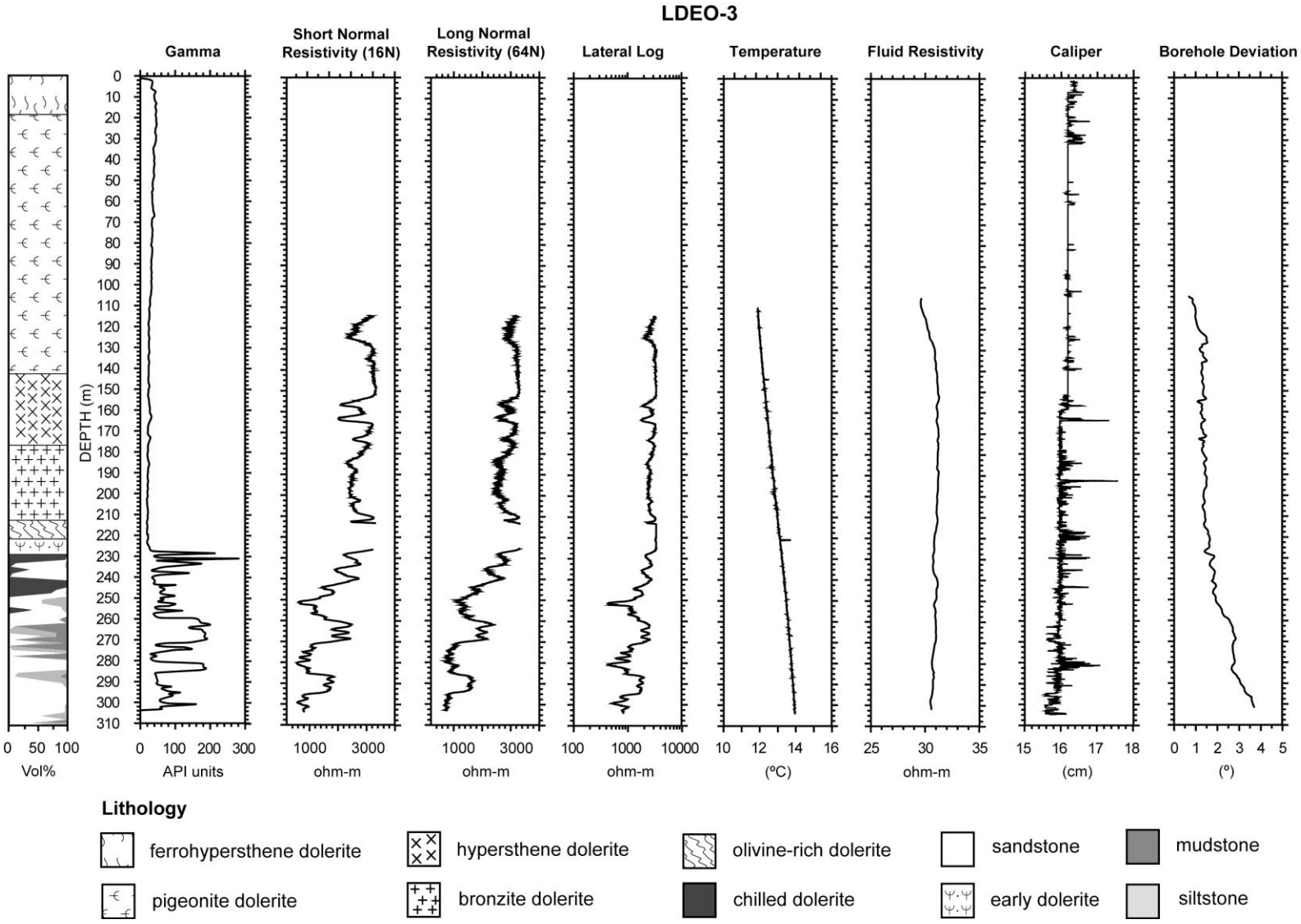
jmatter@ldeo.columbia.edu

Case Study – Lamont Test Wells



Matter et al. (2006)

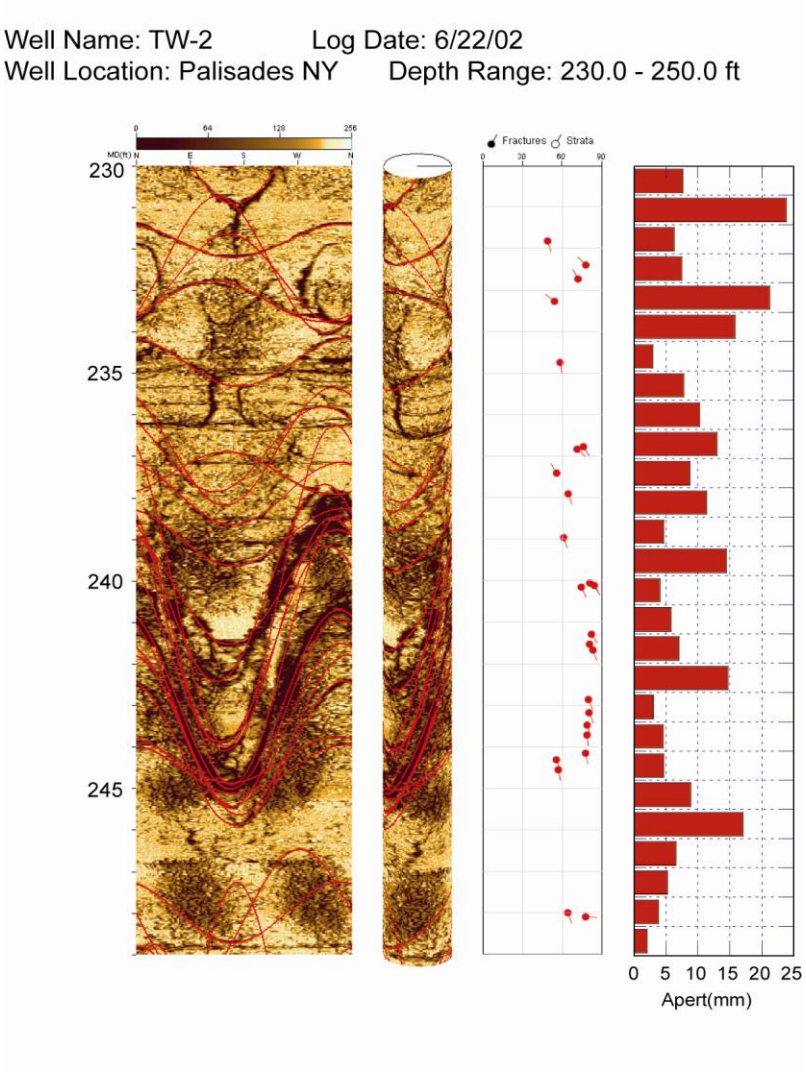
jmatter@ldeo.columbia.edu

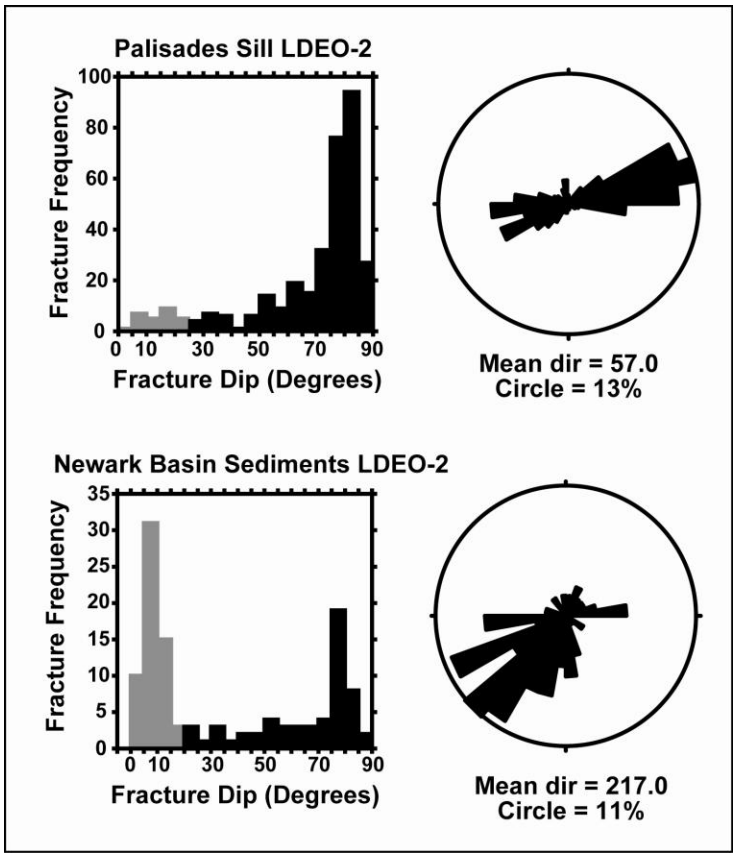


Matter et al. (2006)

jmatter@ldeo.columbia.edu

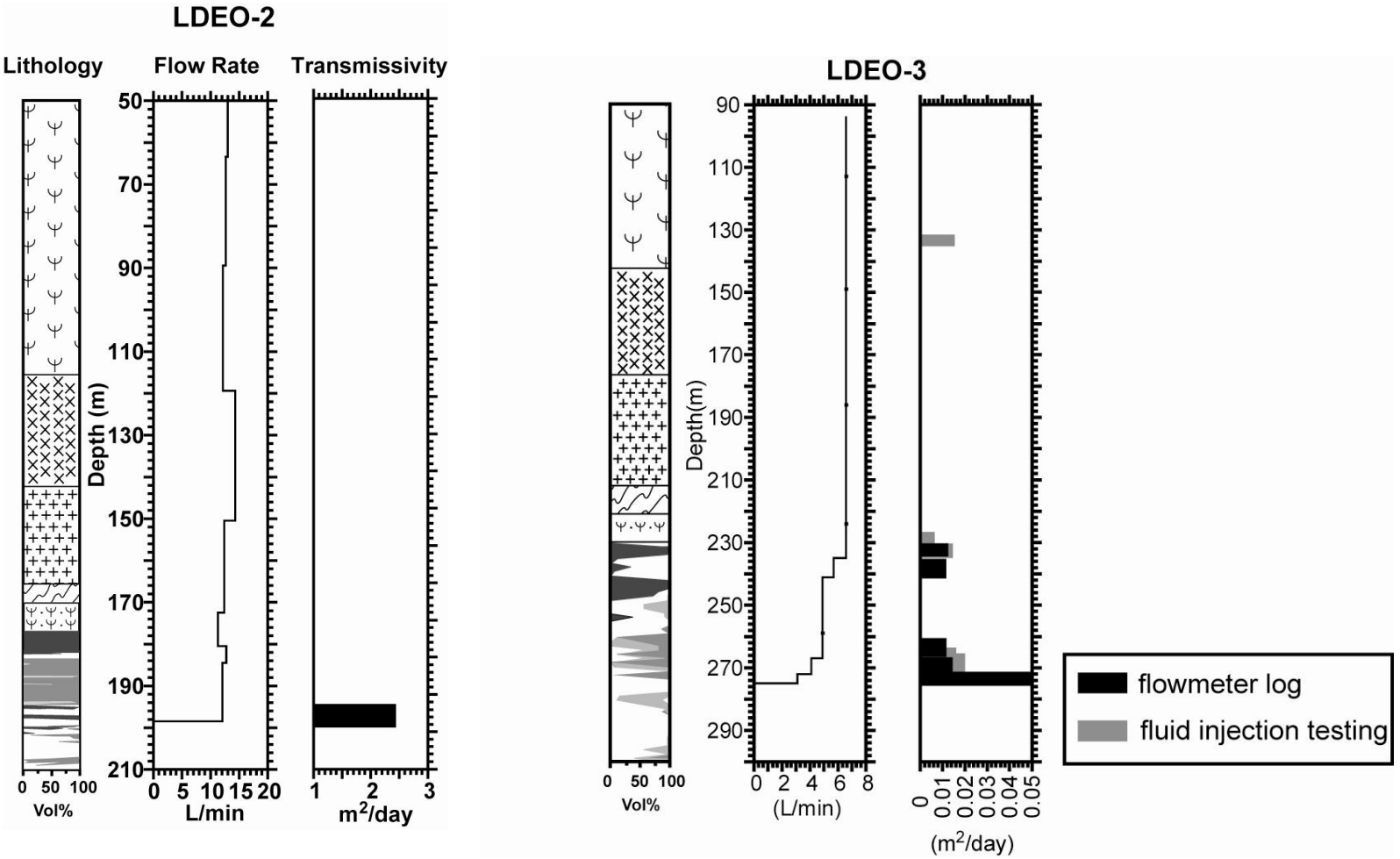
Borehole Televiewer – Lamont Test Wells





jmatter@ldeo.columbia.edu

Flowmeter Logging – Lamont Test Wells



Matter et al. (2006)

jmatter@ldeo.columbia.edu

Flowmeter Log Analysis

- Transmissivity (T) – horizontal flow rate per unit width of aquifer under unit head gradient
- $T = K_h \cdot b$, where b is aquifer thickness
- K_h = horizontal hydraulic conductivity (m/s)
- Cooper and Jacob method (1946)

$$K_1 = \frac{\Delta Q}{2\pi H(\Delta p)} \cdot \ln\left[\frac{2.25 K_2 H t}{R^2 S}\right]^{1/2}$$

Q: horizontal volumetric flow
H: thickness of interval
Δp: change in hydraulic head from static conditions
t: time since onset of pumping or injection
R: borehole radius
S: Storativity (5.5E-05)

jmatter@ldeo.columbia.edu

Permeability Testing

- Short duration fluid injection tests
- Flowmeter measurements with electromagnetic flowmeter
- 48-hour constant discharge pump test

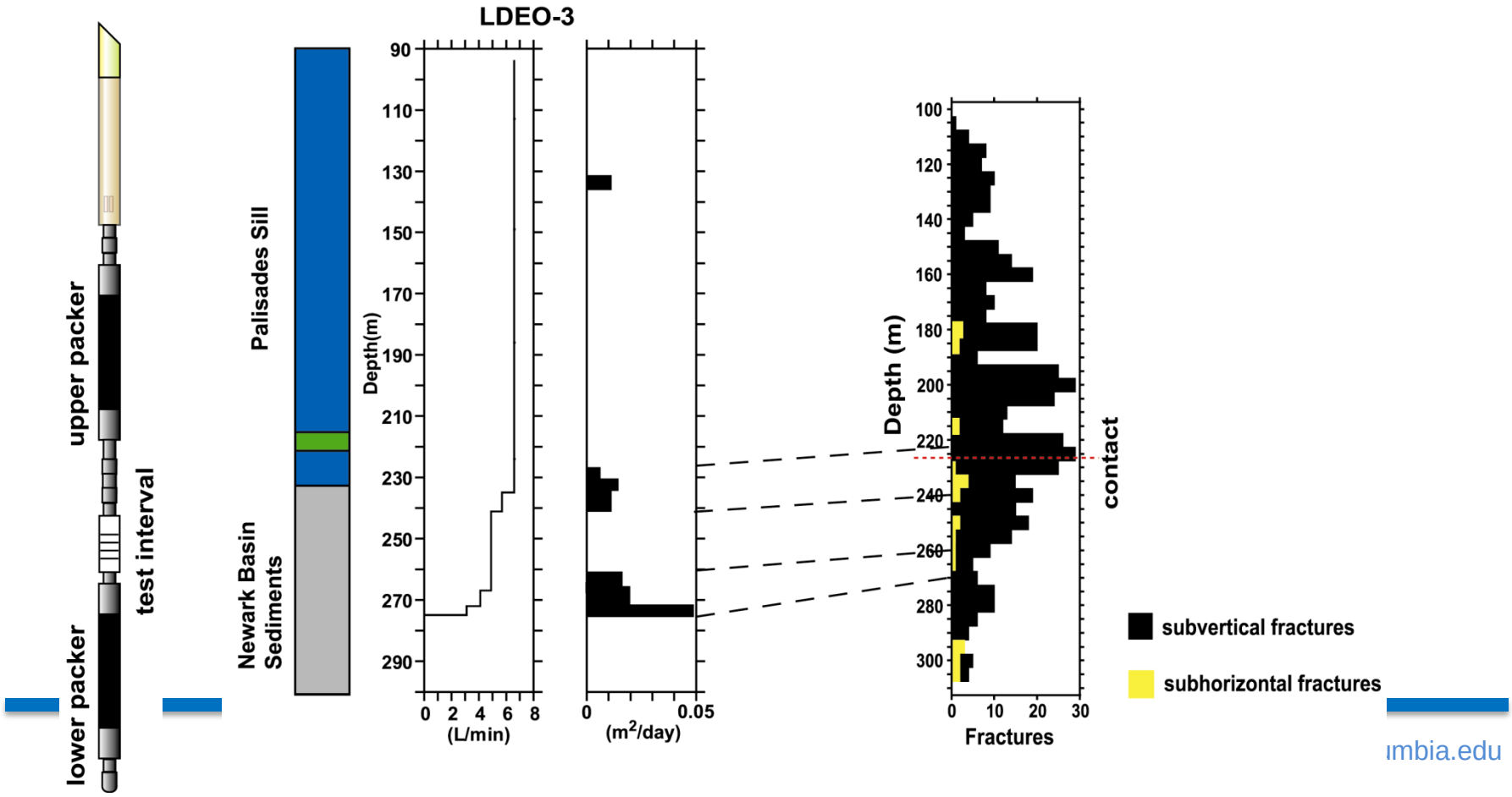


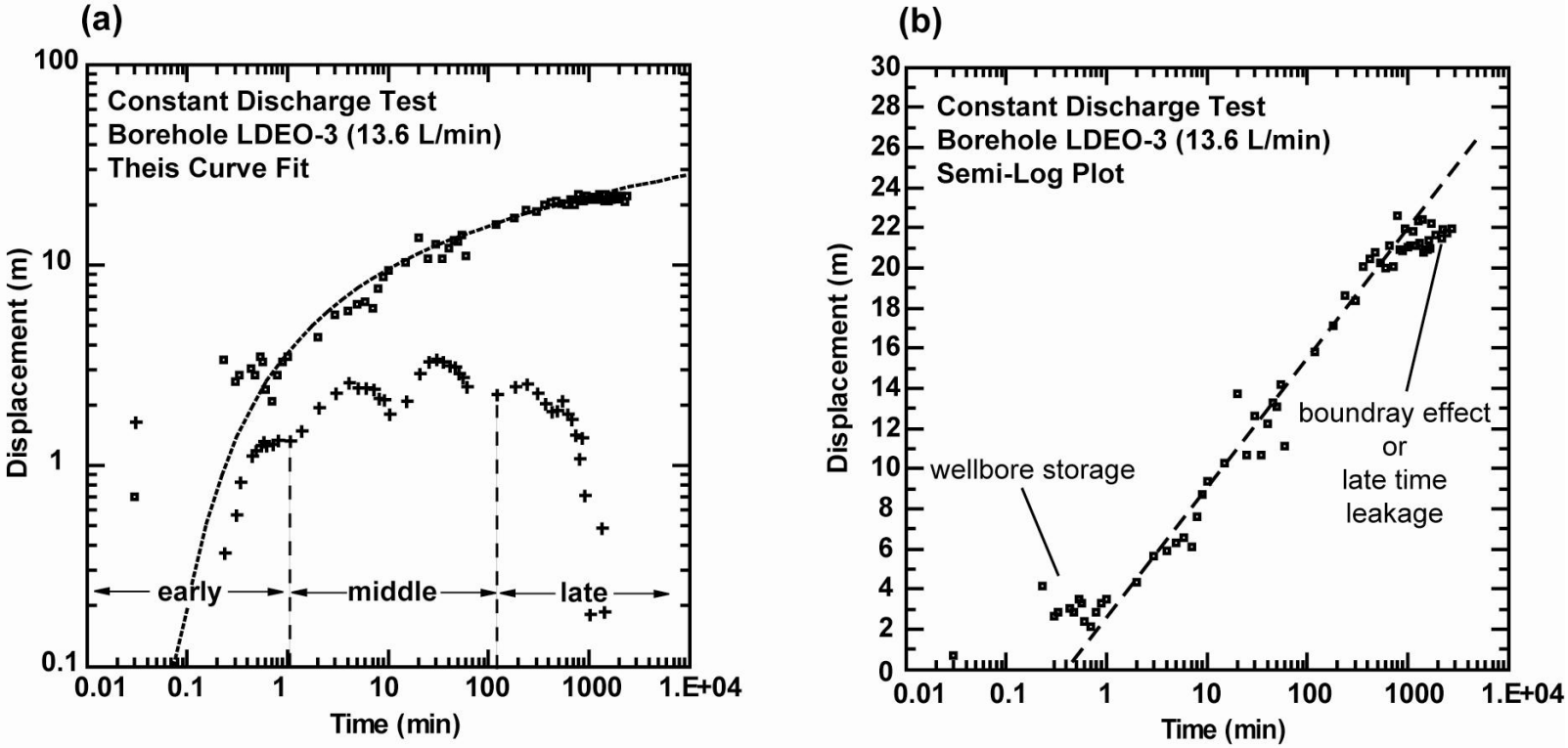
Table 1 Calculated transmissivity values for LDEO-3 based on flowmeter logs, straddle-packer injection, and aquifer tests

	Depth interval (m)	Transmissivity (m^2/s)
Fluid injection	121–124	[a]
	132.5–135.5	3.04E-07
	146–149	[a]
	161.5–164.5	[a]
	170.5–173.5	[a]
	180–183	[a]
	190.5–193.5	[a]
	209.5–212.5	[a]
	214.5–215.5	[a]
	218.5–221.5	[a]
	224.5–234.5	[a]
	227–230	8.10E-08
	231.5–234.5	1.62E-07
	260.5–263.5	[a]
	264–274	2.17E-07
	271–274	[a]
	228–300	9.95E-06
Flowmeter	115–230	[a]
	231–234	1.39E-07
	235–241	1.27E-07
	242–260	[a]
	261–266	1.27E-07
	265–269	1.62E-07
	269–275	5.67E-07
Discharge test	110–227	[a]
	228–300	6.28E-06

[a]Data below detection limit of applied methods

jmatter@ldeo.columbia.edu

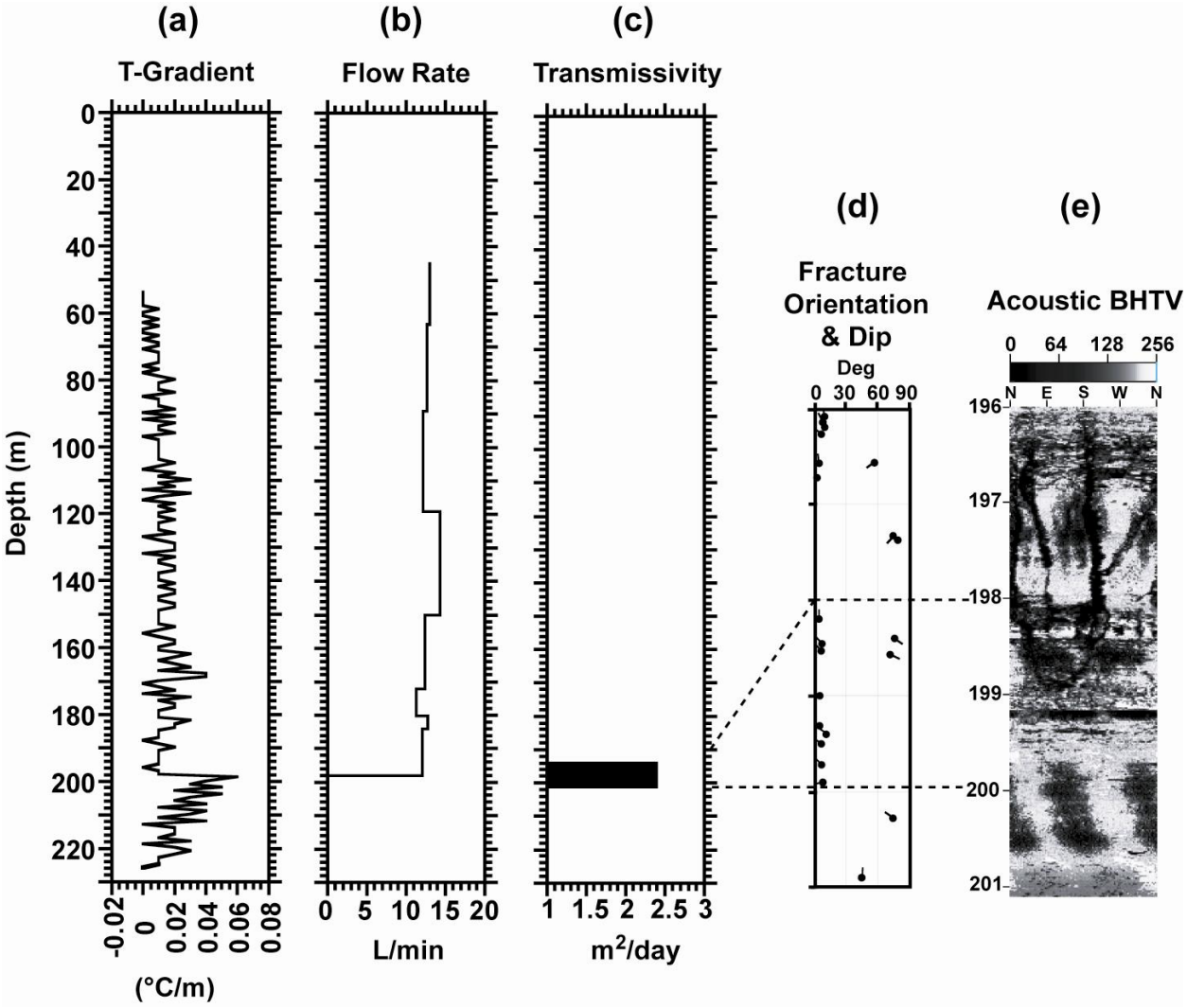
Pump Test Analysis



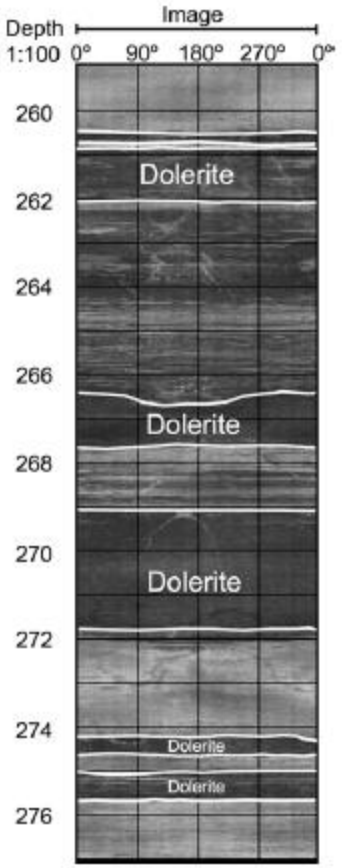
	T (m^2/day)	K (m/day)
Sill	**0.01**	**0.0034**
Contact Zone	**0.02**	**0.006**
N.B. Sediments	**0.57***	**0.0075***

jmatter@ldeo.columbia.edu

Correlation



Optical BHTV



jmatter@ldeo.columbia.edu

Literature

Matter, J. M., D. Goldberg, R. H. Morin, and M. Stute, Contact zone permeability at intrusion boundaries: new results from hydraulic testing and geophysical logging in the Newark Rift Basin, New York, USA.
Molz, F. J., Morin, R. H., Hess, A. E., Melville, J. G., and Guven, O., 1989, The impeller meter for measuring aquifer permeability variations - Evaluations and comparisons with other tests: Water Resources Research, v. 25, p.1677-1683.
Molz, F. J. and Melville, J. G., 1996, Discussion of combined use of flowmeter and time-drawdown data to estimate hydraulic conductivities in layered aquifer systems: Ground Water, v. 34, no. 5, p. 770.
Paillet, F.L., Hess, A.E., Cheng, C.H., and Hardin, E., 1987, Characterization of fracture permeability with high-resolution vertical flow measurements during borehole pumping: Ground Water, v. 25, no. 1, p. 28-40.
Paillet, F.L., 1998, Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations: Water Resources Research, v. 34, no. 5, p. 997-1010.
Paillet, F.L., 2000, A field technique for estimating aquifer parameters using flow log data: Ground Water, v. 38, no. 4, p. 510-521.
Paillet, F.L., and Reese, R.S., 2000, Integrating borehole logs and aquifer tests in aquifer characterization: Ground Water, v. 38, no. 5, p. 713-725.
Paillet, F.L., 2001, Hydraulic head applications of flow logs in the study of heterogeneous aquifers: Ground Water, v. 39, no. 5, p. 667-675.

jmatter@ldeo.columbia.edu