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Ground Water Flow Modeling of Geologically Complex Regional Aquifers

Allen M. Shapiro

U.S. Geological Survey
Reston, VA

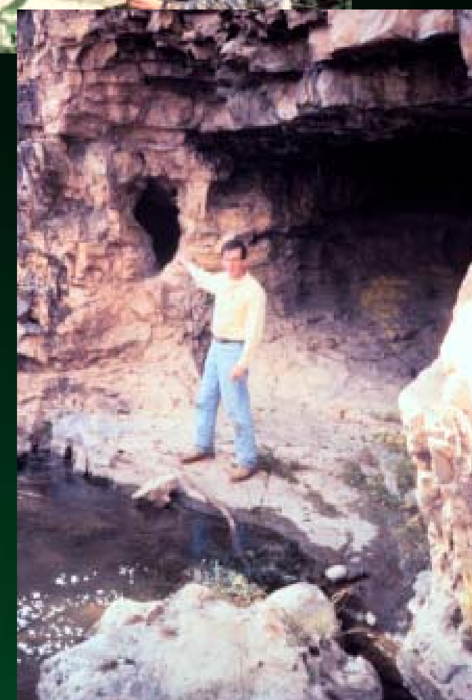
Characterizing complex geologic settings

Granite and schist, Mirror Lake, NH

Dolomite, Argonne, IL

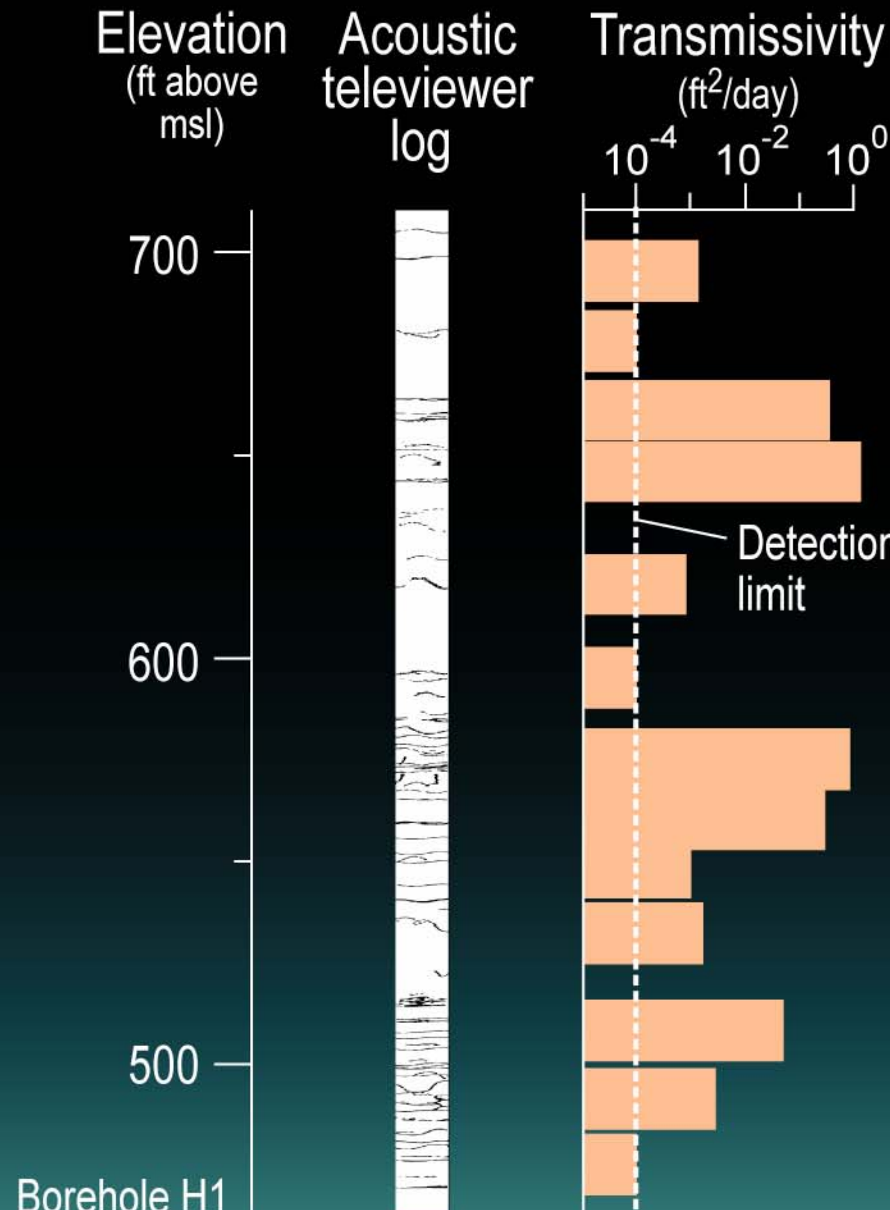
Gneiss, Bethesda, MD

Tonalite, Bethesda, MD



Limestone, Rapid City, SD

Road cut near
Mirror Lake watershed,
New Hampshire



Shapiro and Hsieh, 1998

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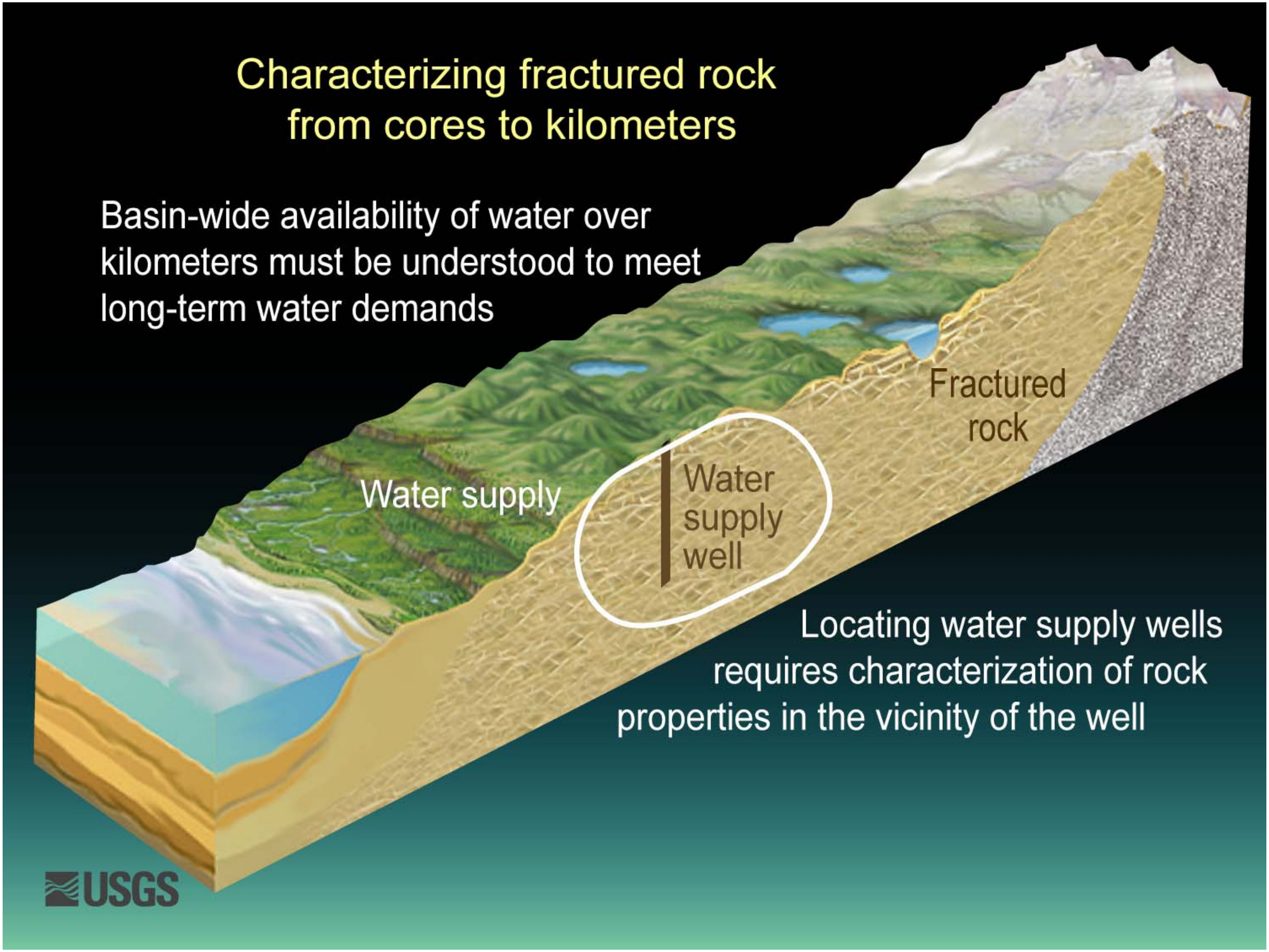
Characterizing fractured rock
from cores to kilometers
Basin-wide availability of water over kilometers must be understood to meet long-term water demands
Water supply
Water supply well
Fractured rock
Locating water supply wells requires characterization of rock properties in the vicinity of the well
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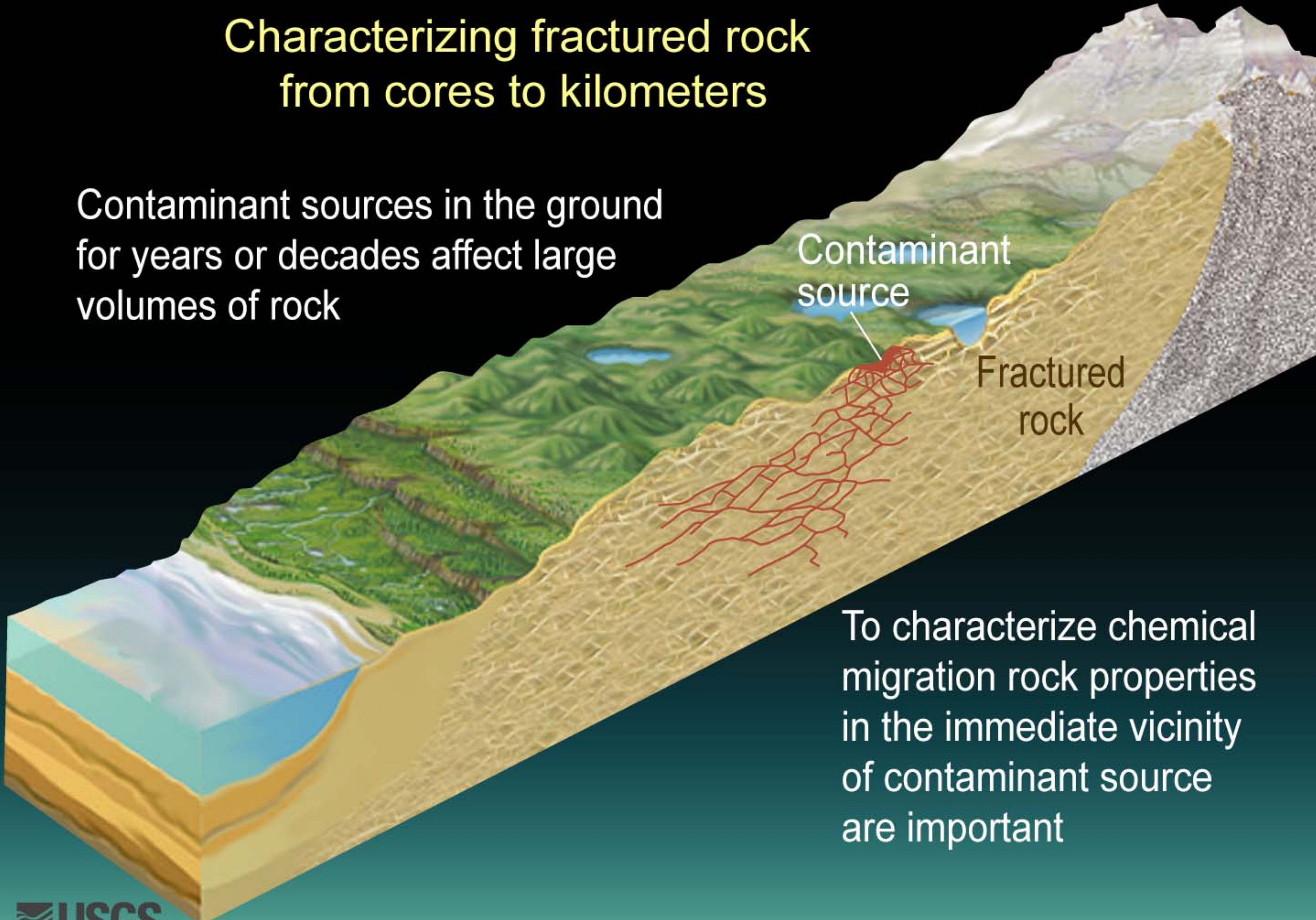
Characterizing fractured rock from cores to kilometers

Contaminant sources in the ground for years or decades affect large volumes of rock



To characterize chemical migration rock properties in the immediate vicinity of contaminant source are important

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Ground-Water Modeling is an Important Tool in Water Resources Management in Geologically Complex Aquifers

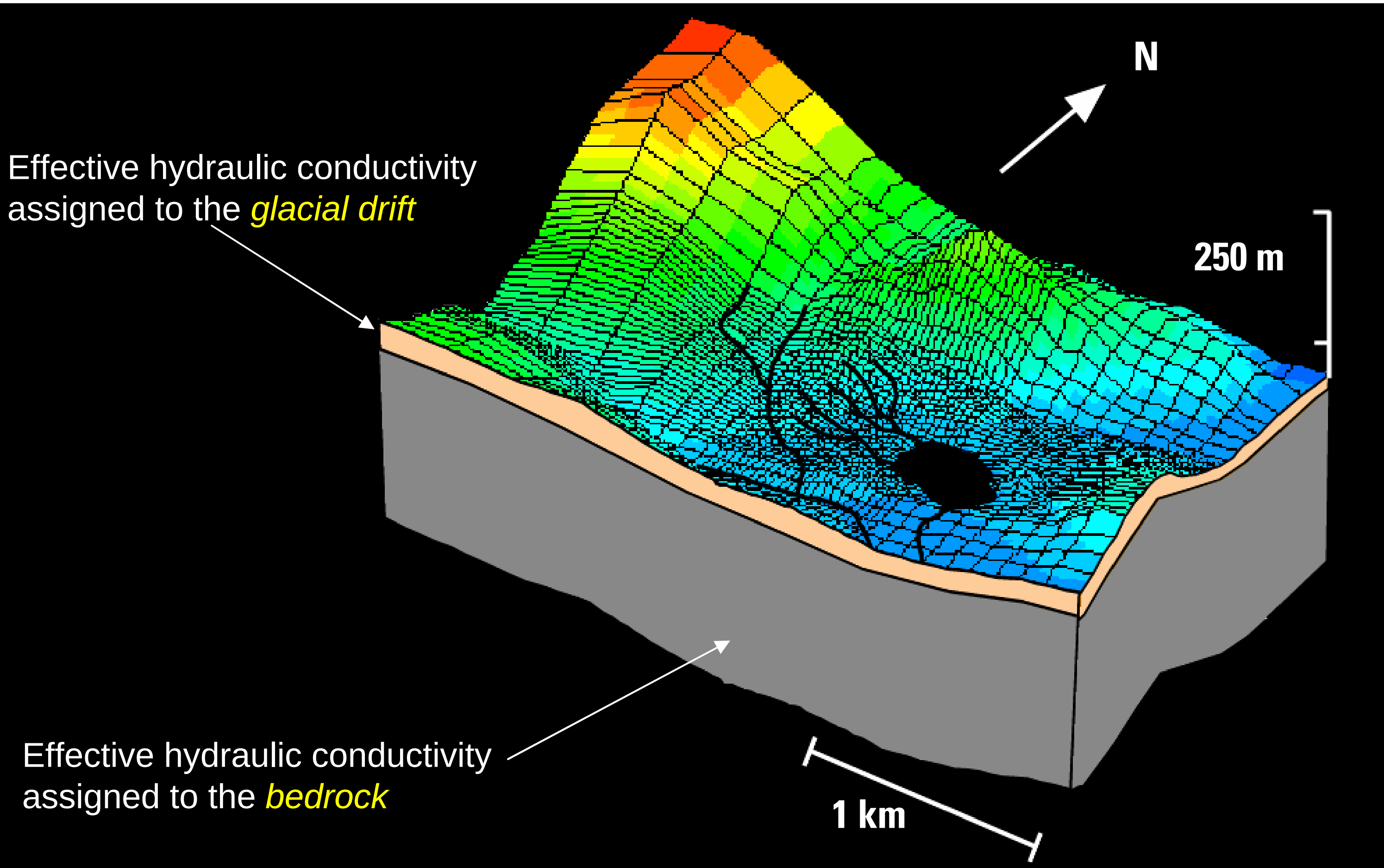
Ground-water modeling can aid in identifying important geological, physical, and chemical processes. . .

Ground-water modeling can be used in predicting scenarios of aquifer management prior to their implementation. . .

Ground-water modeling can assist in designing data collection efforts. . .

Ground-water modeling can be used in identifying the most sensitive aquifer parameters and regions of greatest importance to project objectives. . .

The limitations of ground-water modeling must be recognized to fulfill project objectives effectively. . .



This ground-water flow model can characterize regional ground-water flow, but will not be able to resolve the flow regime in the vicinity of an individual bedrock well with any degree of accuracy. . .

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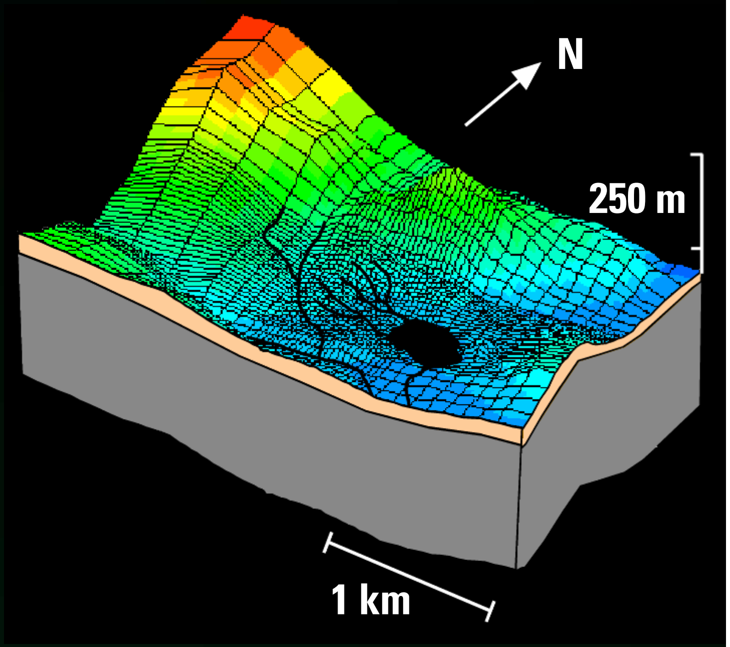


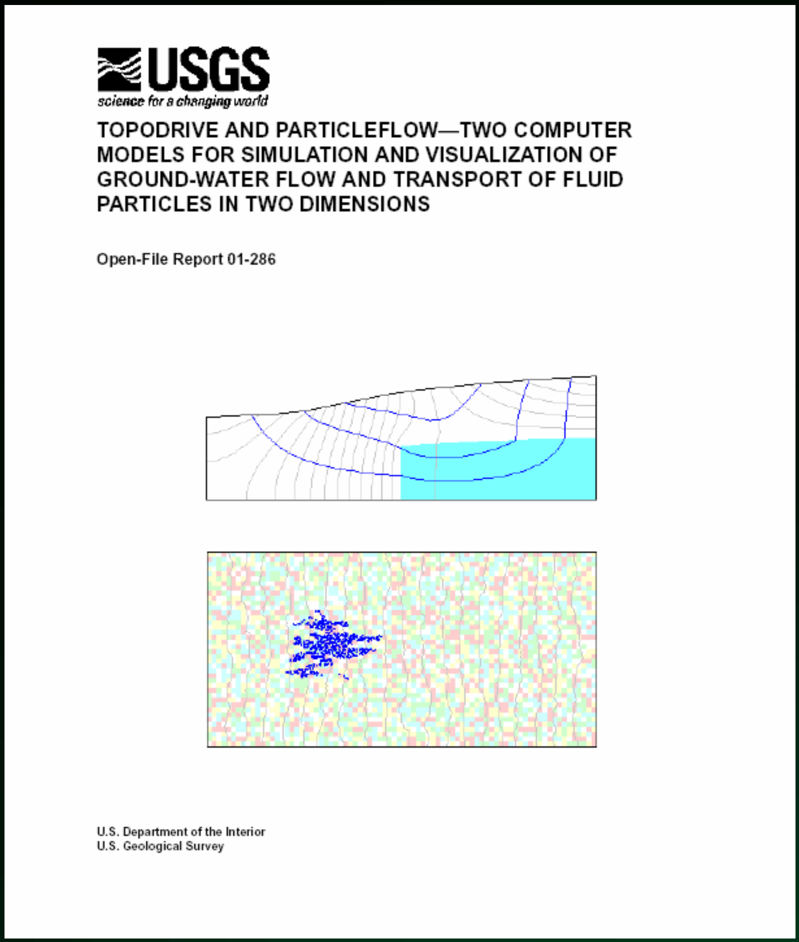
A simple application of ground-water flow modeling. . . *reconnaissance model*

Topography strongly controls ground-water flow

Topography controls locations of ground-water discharge

Topography controls the configuration of the water table

Modeling Software - TOPODRIVE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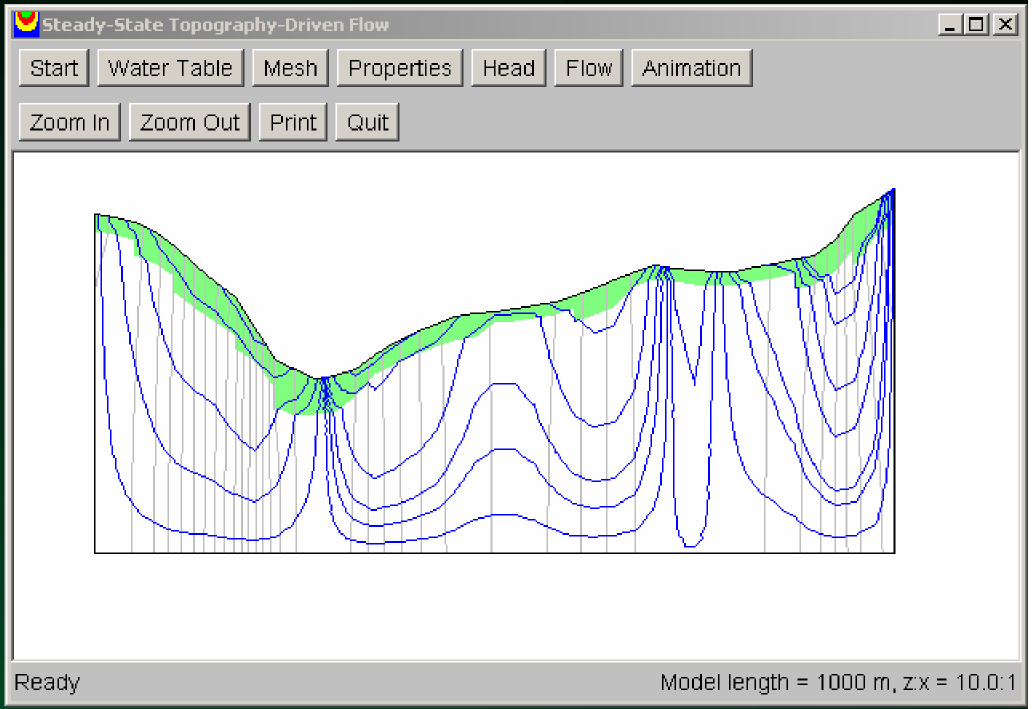
TOPODRIVE AND PARTICLEFLOW—TWO COMPUTER MODELS FOR SIMULATION AND VISUALIZATION OF GROUND-WATER FLOW AND TRANSPORT OF FLUID PARTICLES IN TWO DIMENSIONS

Open-File Report 01-286

U.S. Department of the Interior
U.S. Geological Survey



Ground-Water Modeling and Project Objectives

Ground-water modeling can only be discussed in the context of project objectives. . .

It is impossible to develop one model that will answer all questions. . .

Multiple models may be needed to fulfill project objectives . . .

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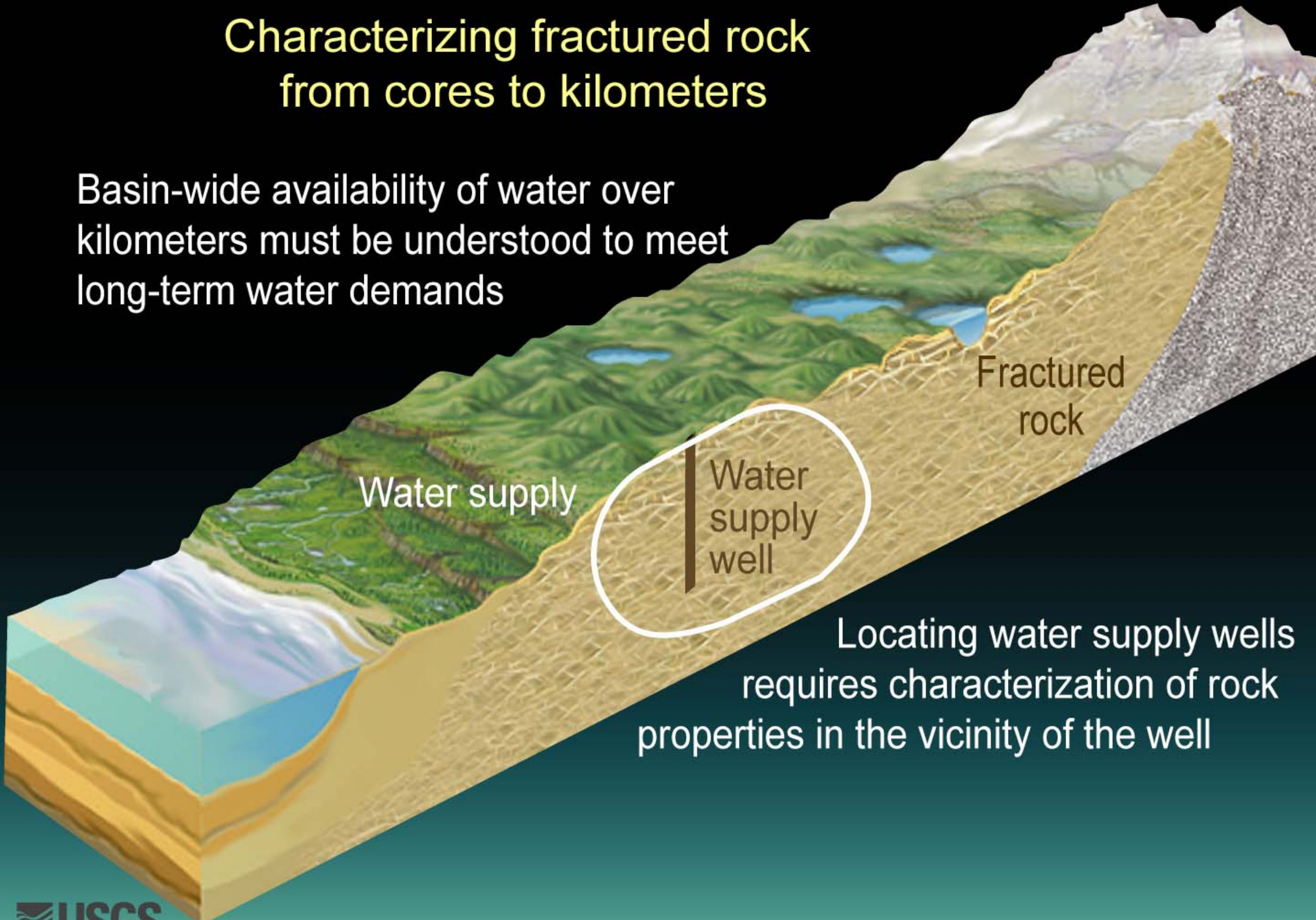
Characterizing fractured rock from cores to kilometers

Basin-wide availability of water over kilometers must be understood to meet long-term water demands



Locating water supply wells requires characterization of rock properties in the vicinity of the well

Ground-Water Modeling and Project Objectives

Characterizing processes affecting regional ground-water flow

an example. . .the Guarani Aquifer System (Brazil, Argentina, Paraguay and Uruguay). . .

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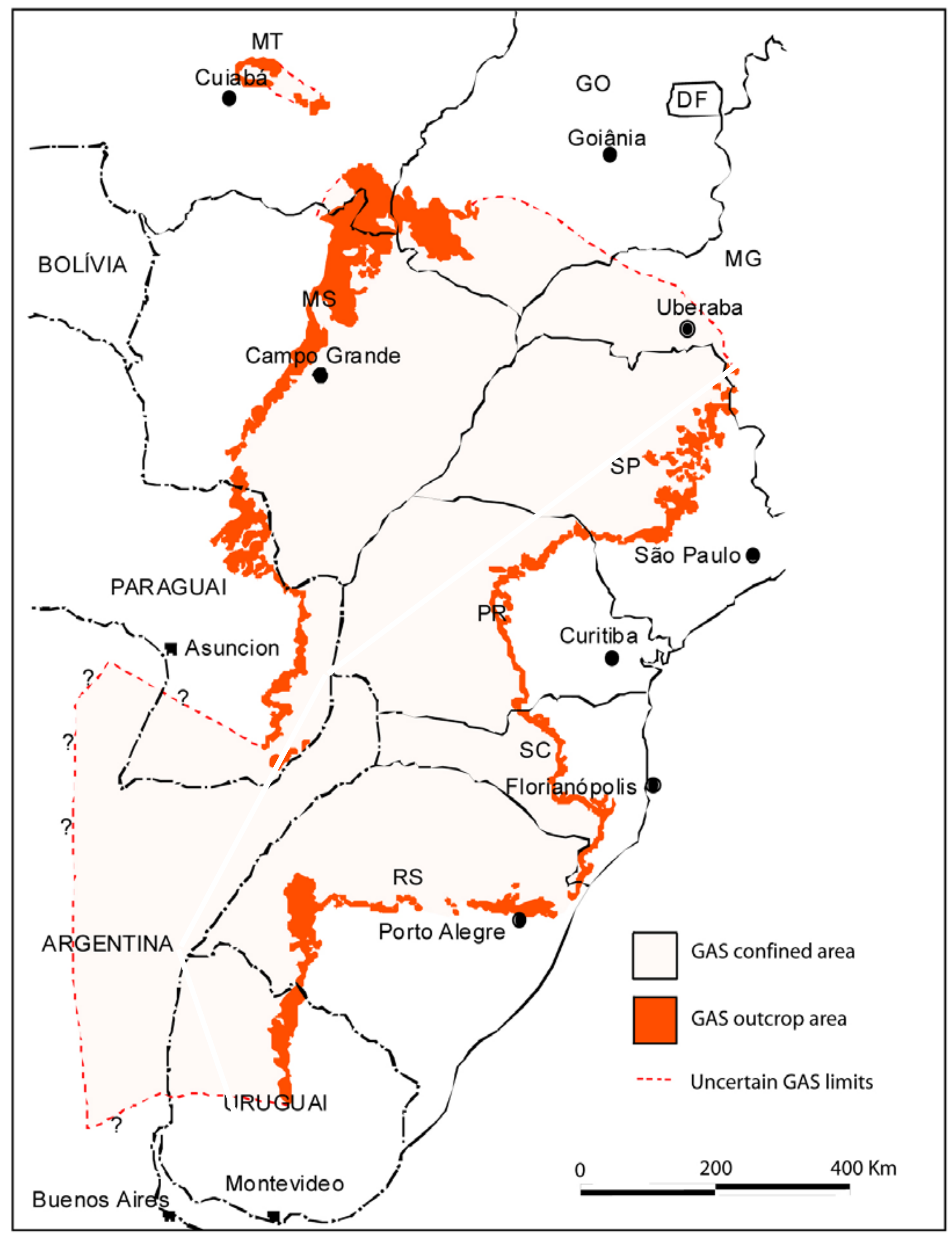
Guarani Aquifer System - GAS



Rosa Filho *et al.* 2001

Importance of the Guarani

- Transboundary aquifer: Argentina, Brazil, Paraguay and Uruguay
- Total area of almost 1.2 Mkm^2
- About 15 million people live on the aquifer area
- Total groundwater production of the GAS is estimated to be in the range of 1 – 3,000 Mm^3/a (80% for public water supply, 15% for industry and 5% for spa tourist use
- 500 Brazilian cities are wholly or partially supplied from the aquifer

(The World Bank 2004)

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Serra Geral Aquifer

Serra Geral Formation – Eo-Cretaceous (130-120 Ma)

- Largest lava flow in the world (>1,000,000 km^2 ~ 390,000 mi^2)
- Fine grained to aphanitic tholeitic basalts (mainly labradorite and augite)
- Thickness of up to 1,930 m (west São Paulo State)
- Transmissivity: $1e^{-5}$ to $4\ e^{-4}$ m^2/s
- Effective porosity: 1 to 5%

(DAEE 1974, Fili *et al.* 1998, Montenegro *et al* 1988)

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Problems

- Controversy on the existence of recharge of the Guarani Aquifer System (GAS) through the basalt cover
- Land occupation regulation only considers the sandstone outcrops as recharge areas for the GAS
- Exact pathways and magnitude of recharge through the basalts remain unknown
- Implications: groundwater management issues (recharge / contamination)

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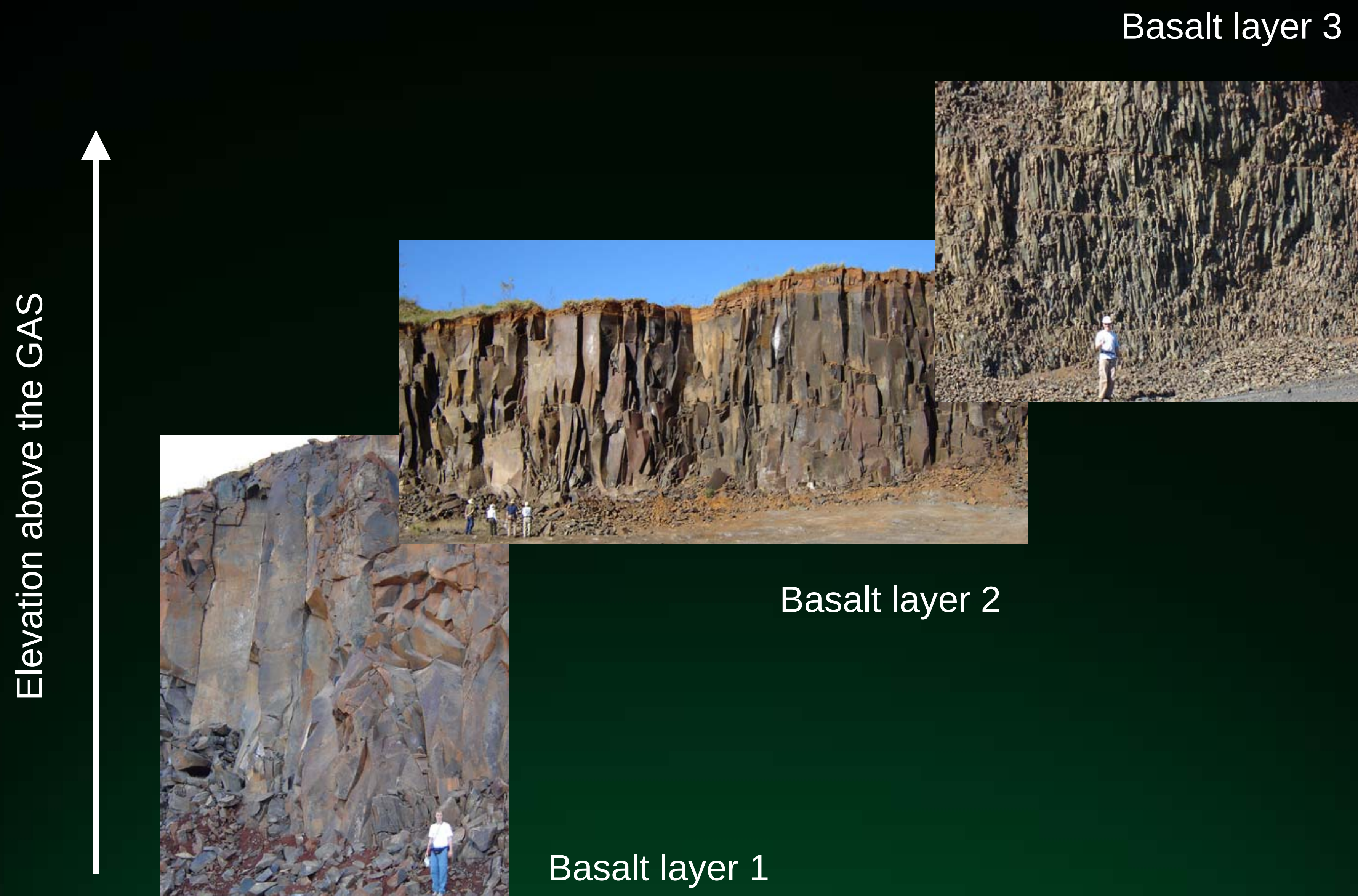
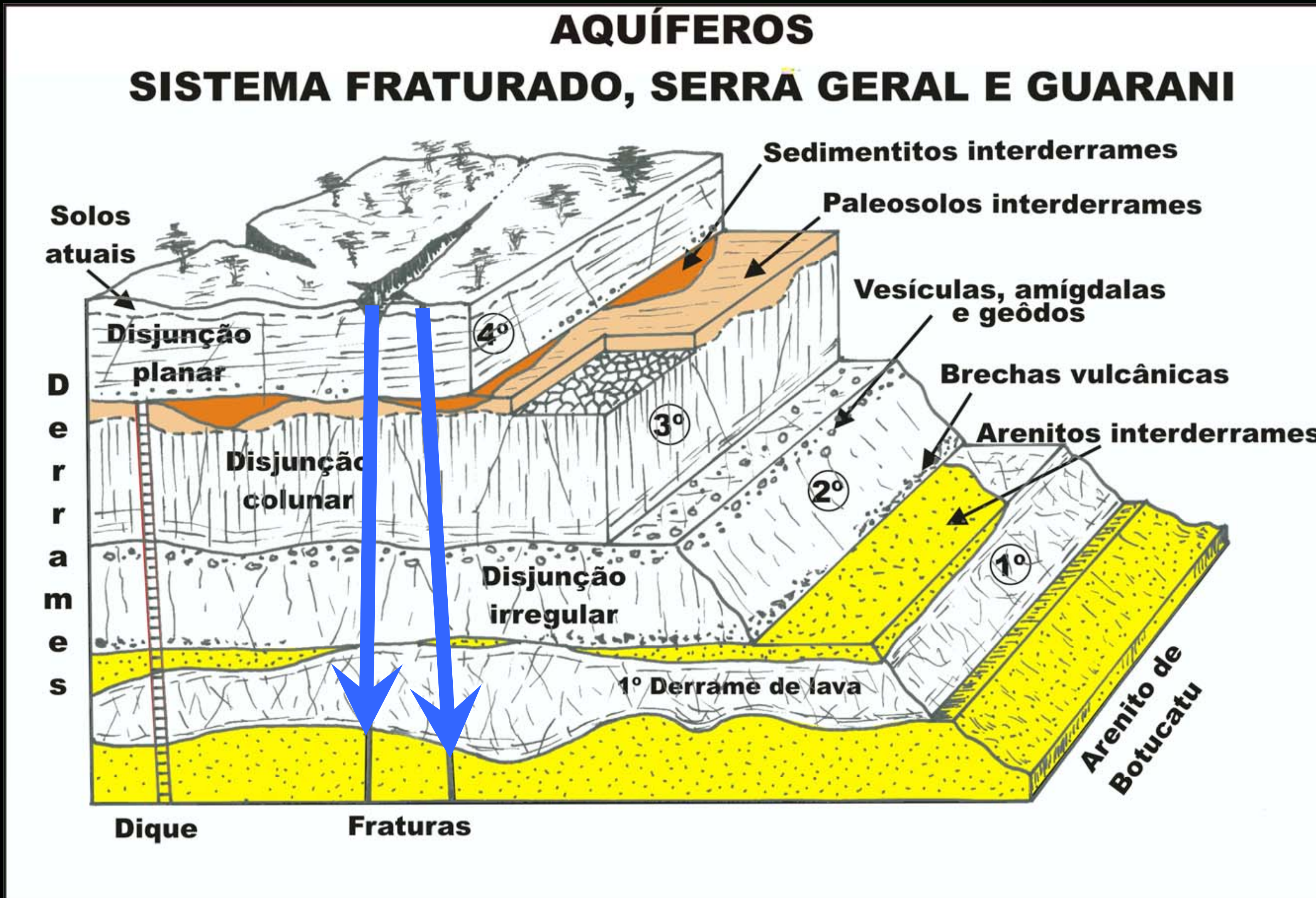
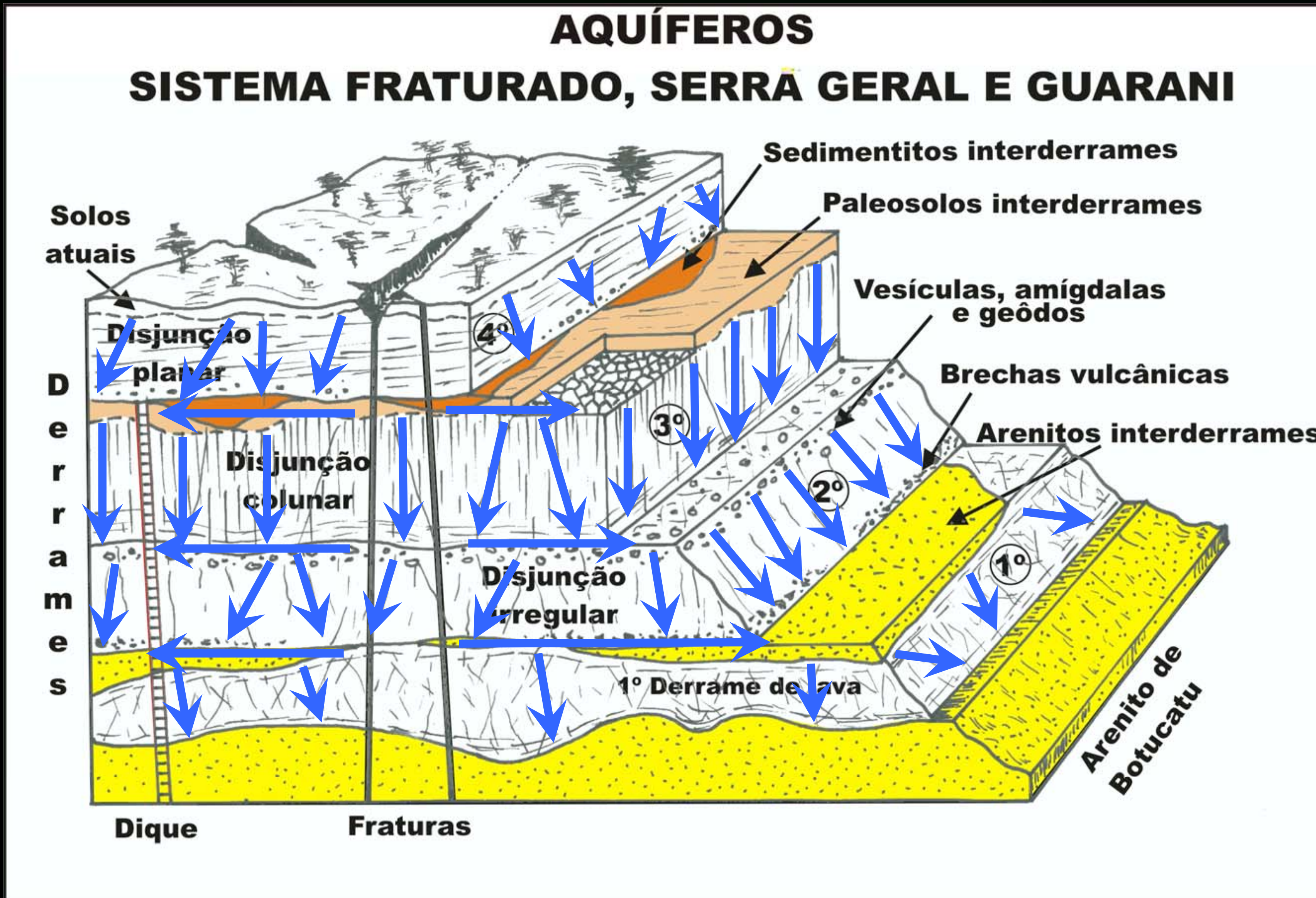

Basalt layer 3
Basalt layer 2
Basalt layer 1
Elevation above the GAS

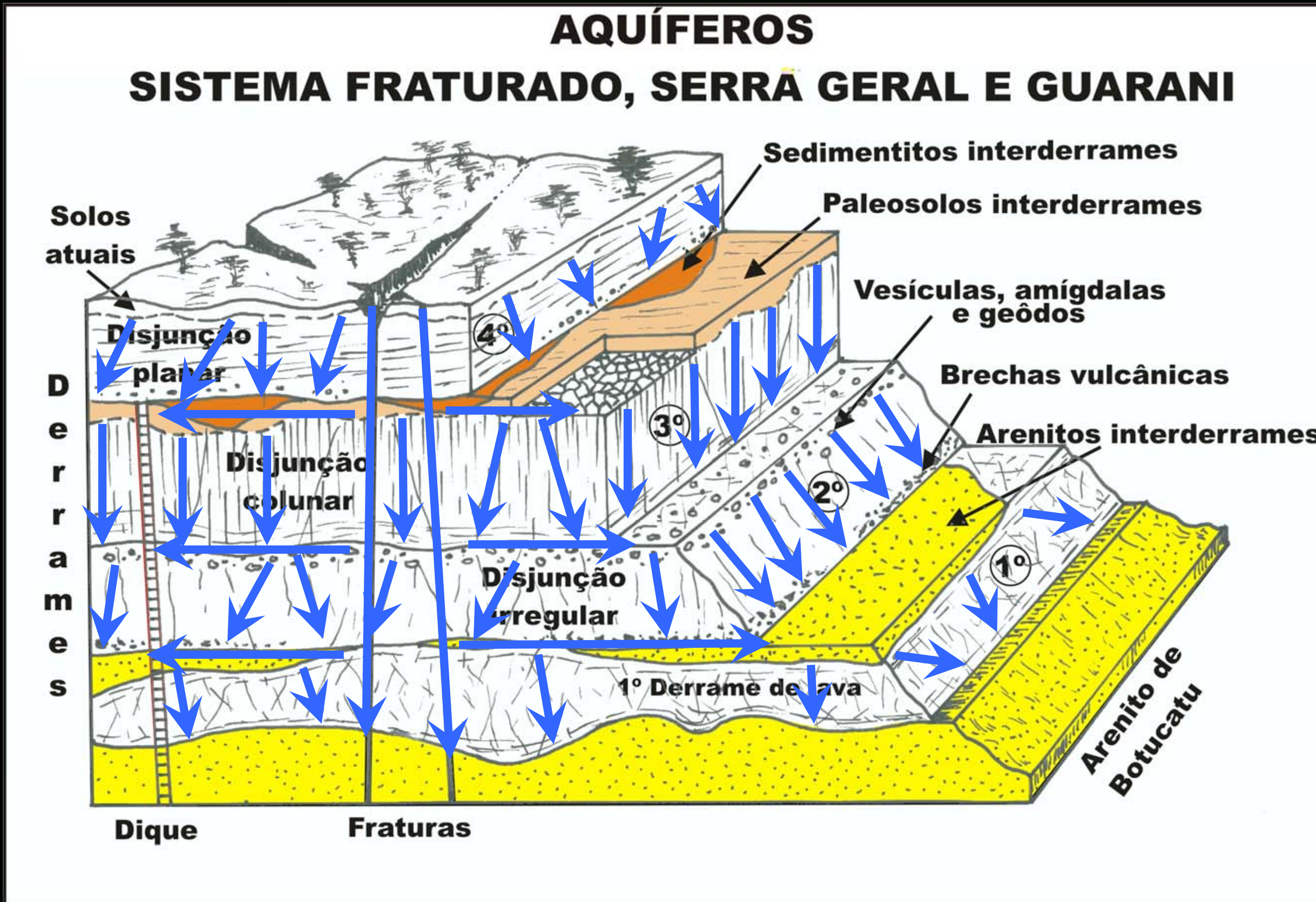
Recharge to the GAS - Discrete features



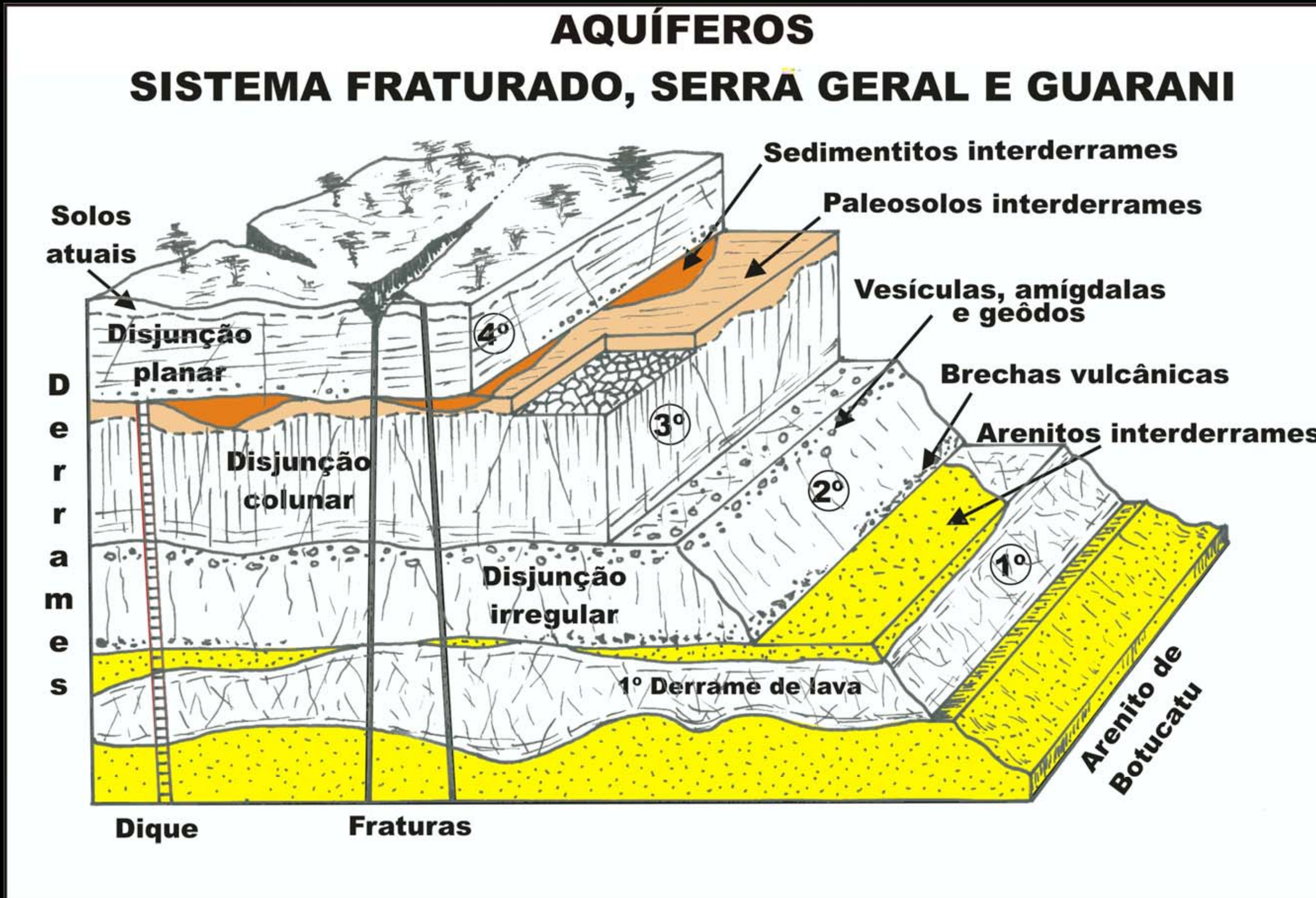
Recharge to the GAS - Areally distributed



Recharge to the GAS - Both



Recharge to the GAS - None ?



Ground-Water Modeling and Project Objectives

Characterizing processes affecting regional ground-water flow

What type of data collection effort is needed to identify the magnitude of recharge, pathways of recharge, residence time of ground water, etc. ?

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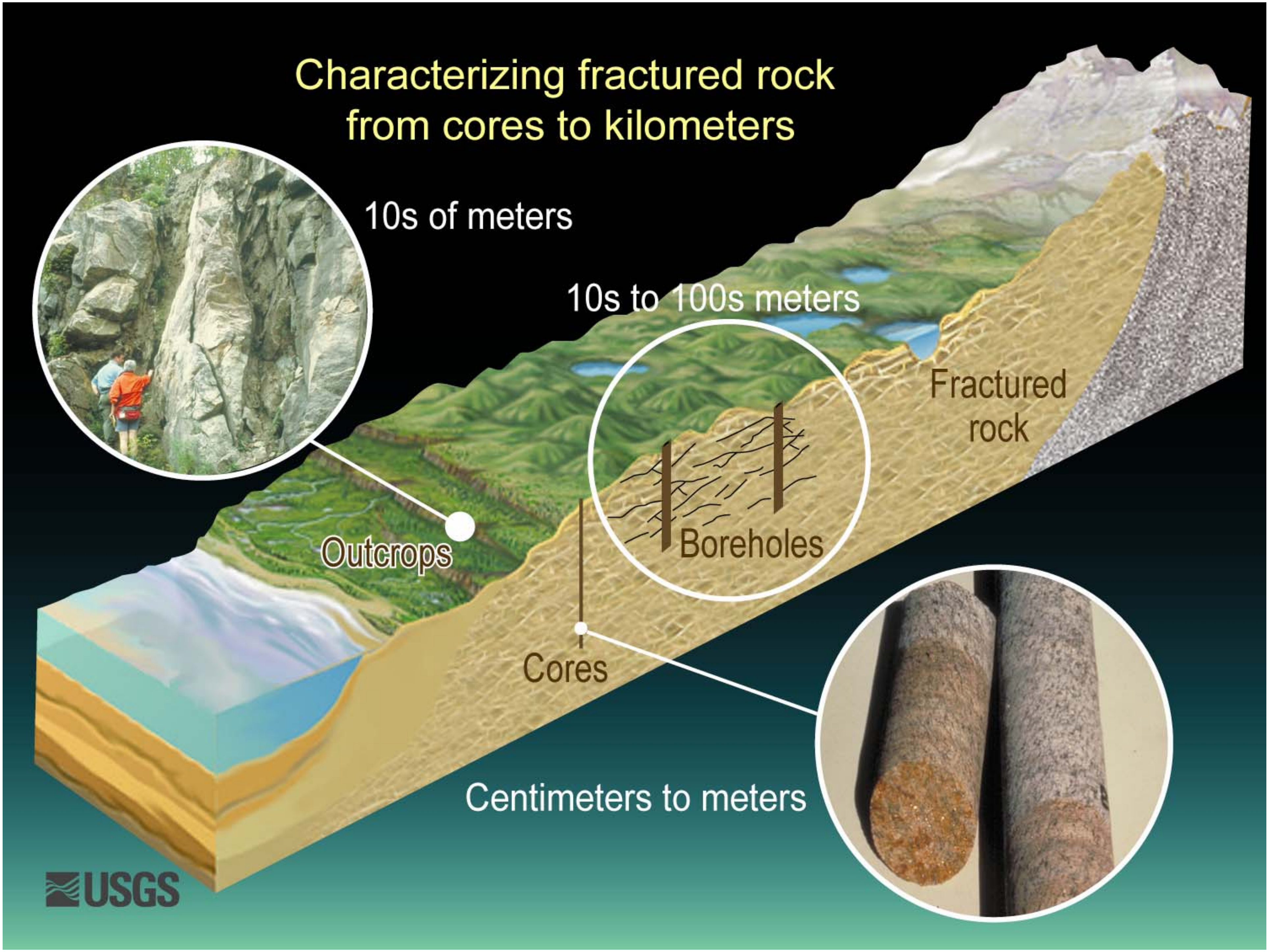
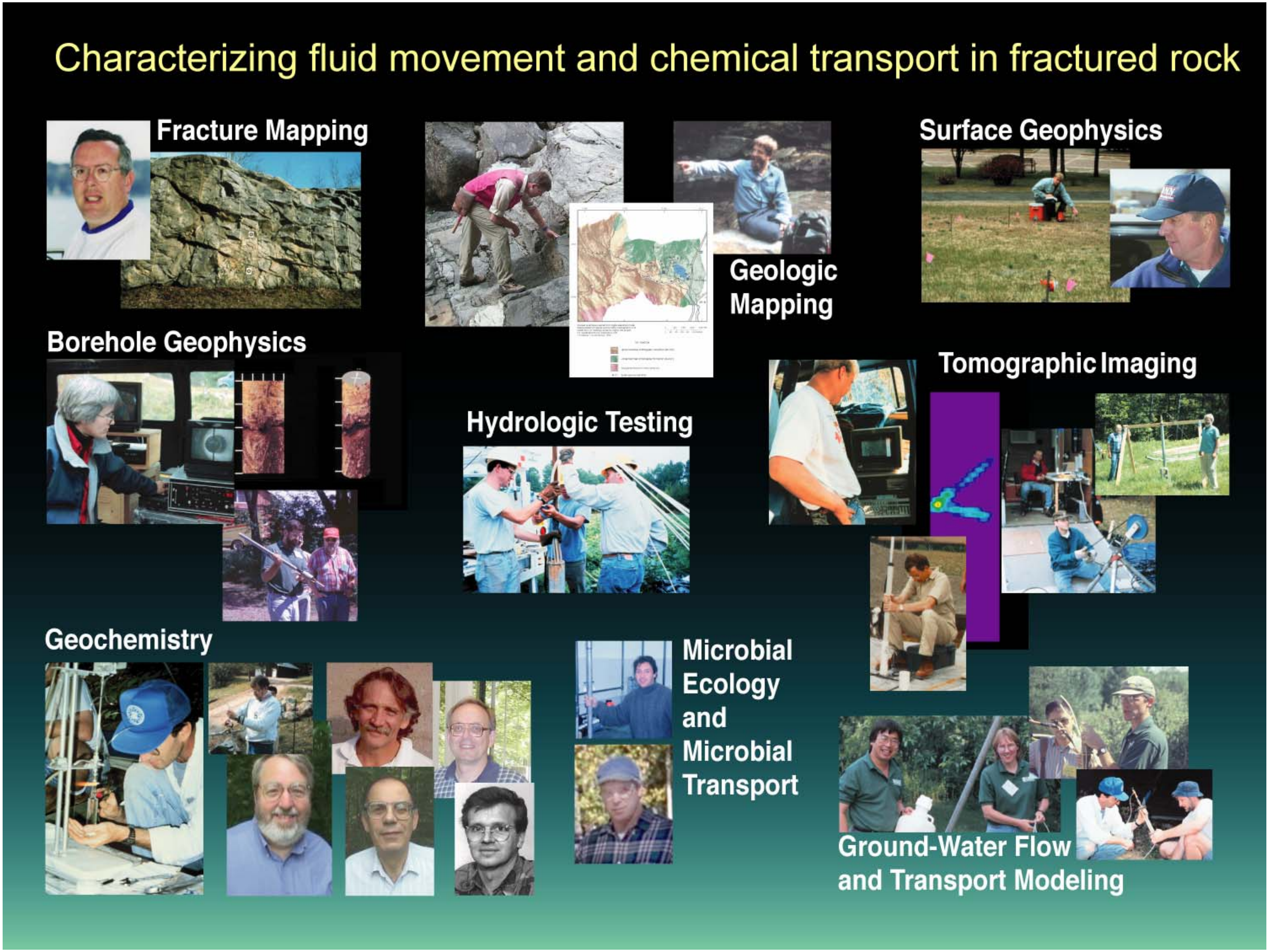

Characterizing fractured rock
from cores to kilometers
10s of meters
10s to 100s meters
Fractured
rock
Outcrops
Boreholes
Cores
Centimeters to meters
USGS



Characterizing fluid movement and chemical transport in fractured rock
Fracture Mapping
Geologic Mapping
Surface Geophysics
Borehole Geophysics
Tomographic Imaging
Hydrologic Testing
Geochemistry
Microbial Ecology and Microbial Transport
Ground-Water Flow and Transport Modeling

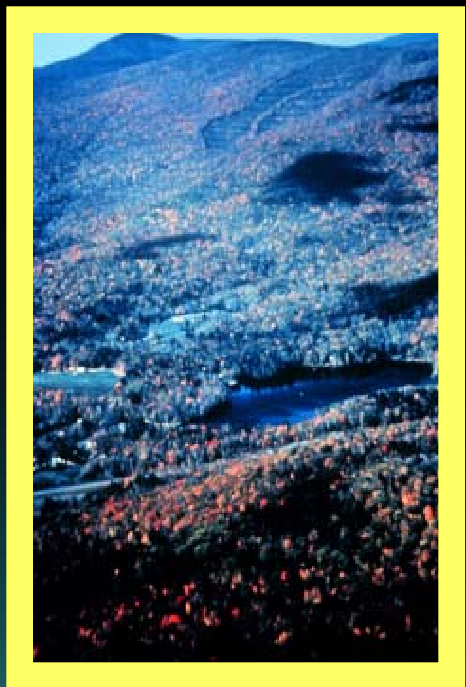
Mirror Lake research site in central New Hampshire

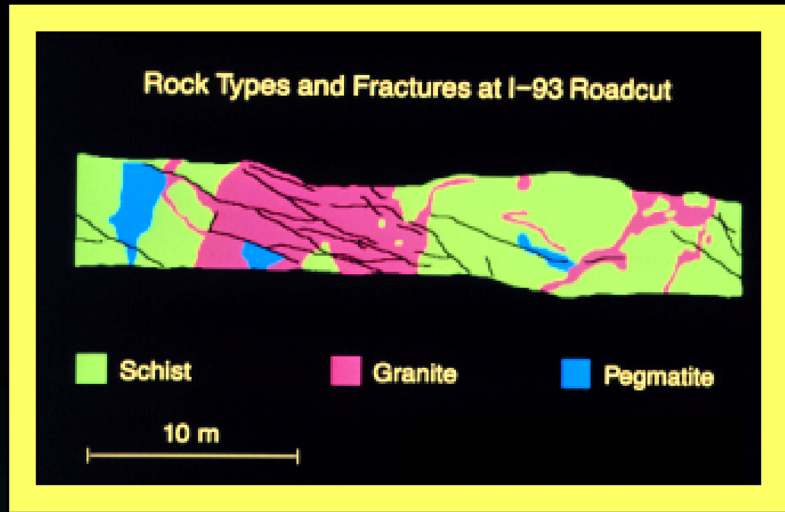
Supported by

USGS Toxic Substances Hydrology Program
http://toxics.usgs.gov/

USGS National Research Program
http://water.usgs.gov/nrp/

Mirror Lake research site in central New Hampshire





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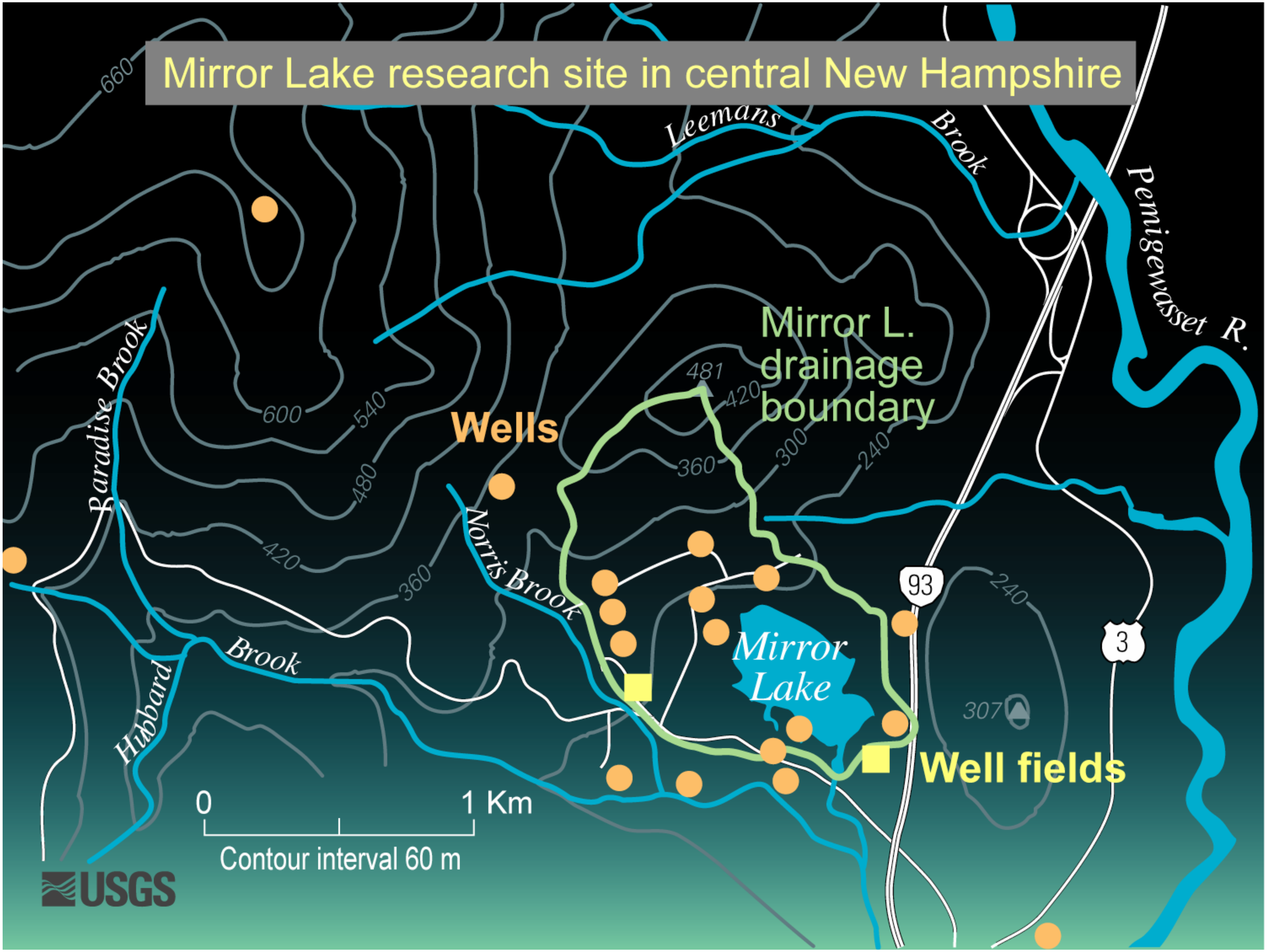
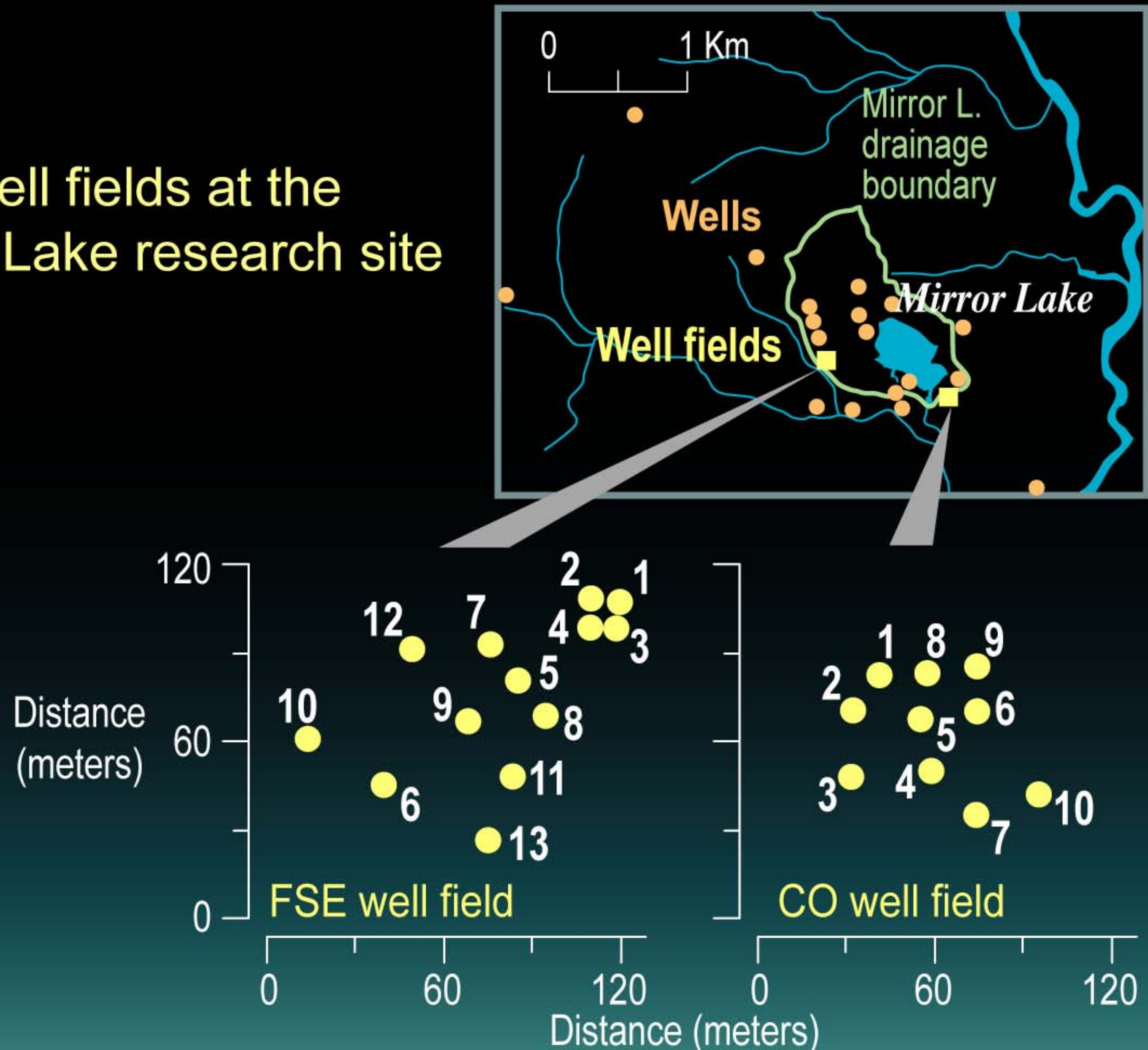


Mirror Lake research site in central New Hampshire
Leemans
Brook
Pemigewasset R.
Paradise Brook
Hubbard
Brook
Norris Brook
Mirror L. drainage boundary
Wells
Mirror Lake
Well fields
93
3
660
600
540
480
420
360
481
420
360
300
240
240
307
0
1 Km
Contour interval 60 m
USGS

Well fields at the Mirror Lake research site



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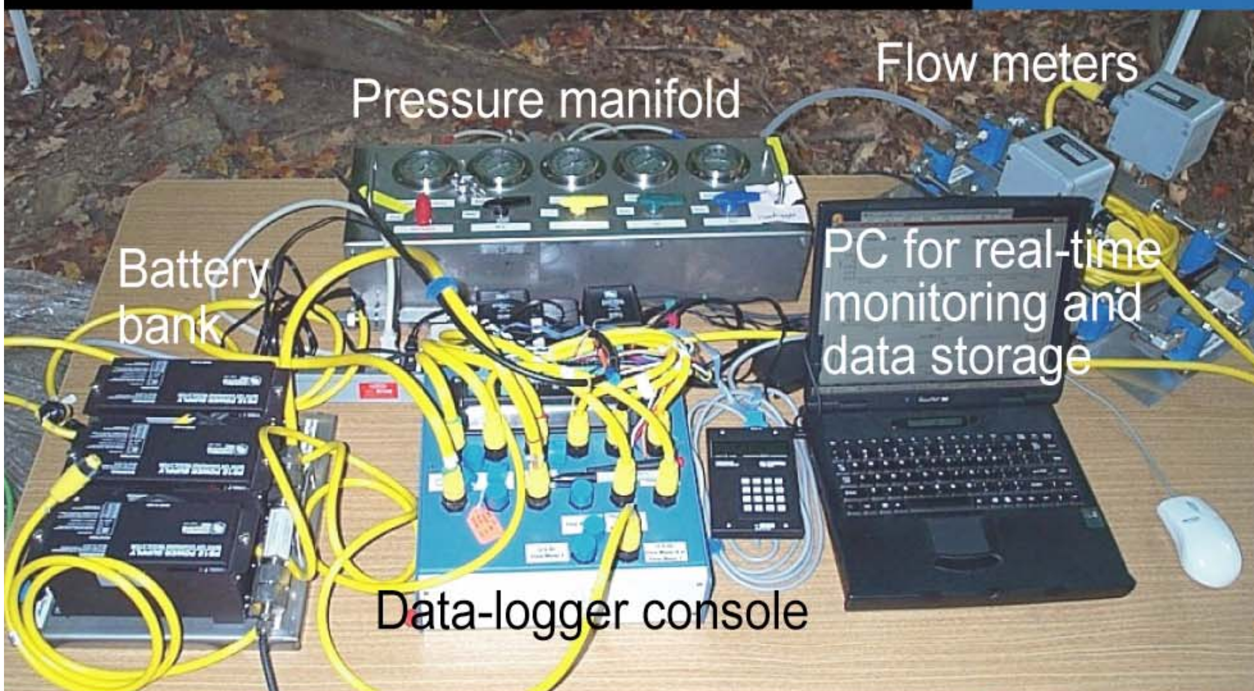
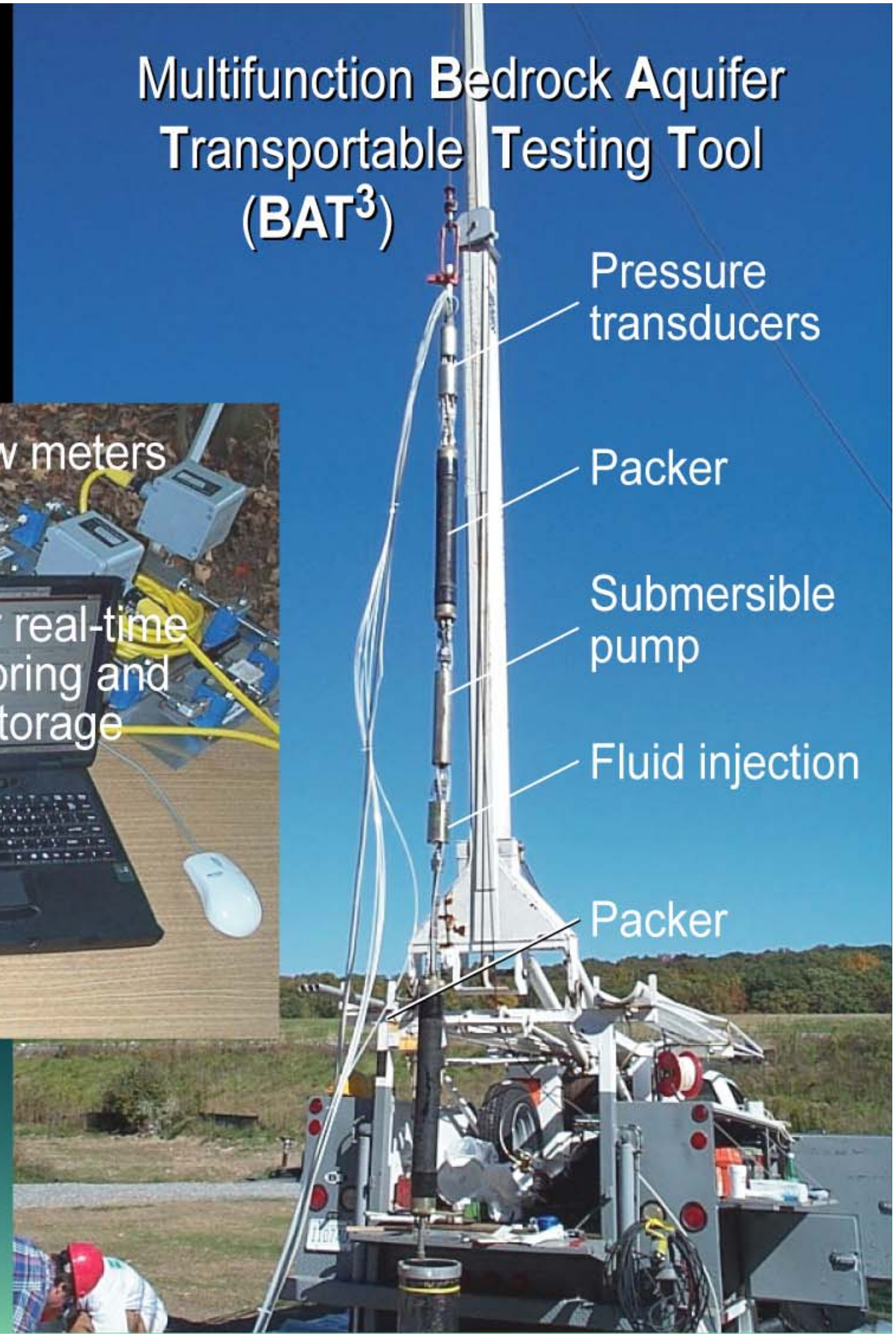
Characterizing hydraulic properties over meters





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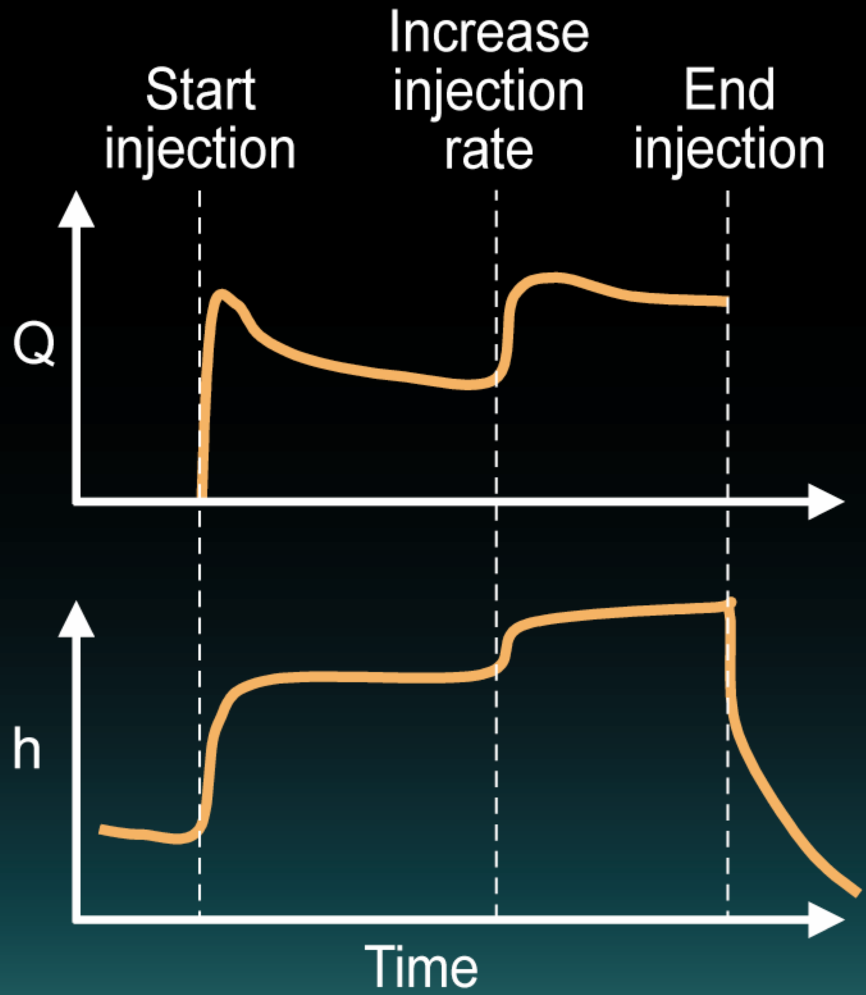
Hydraulic responses measured from hydraulic tests



Estimating transmissivity of the test interval

$$Q = 2\pi r T \frac{dh}{dr}$$

$$T = \frac{Q}{2\pi \Delta h} \ln\left(\frac{R}{r_s}\right)$$

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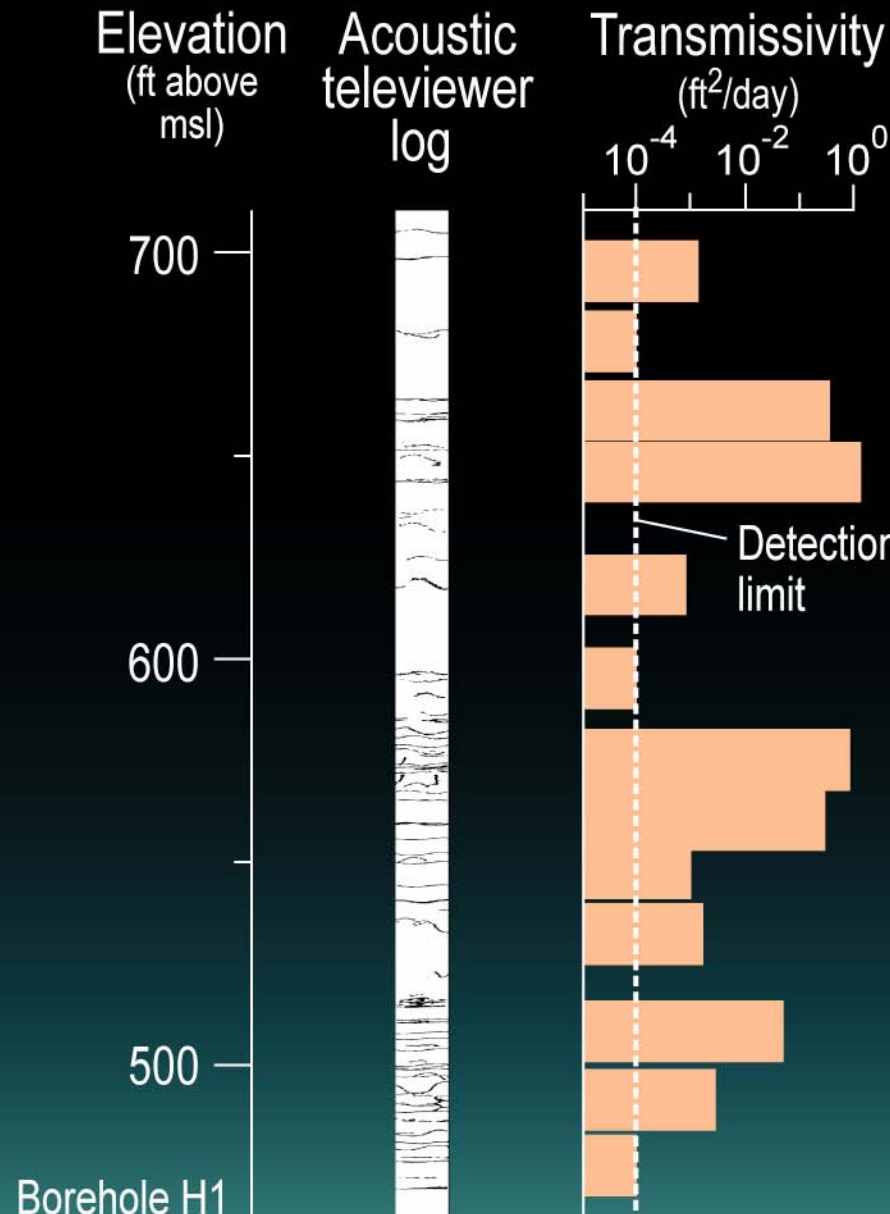
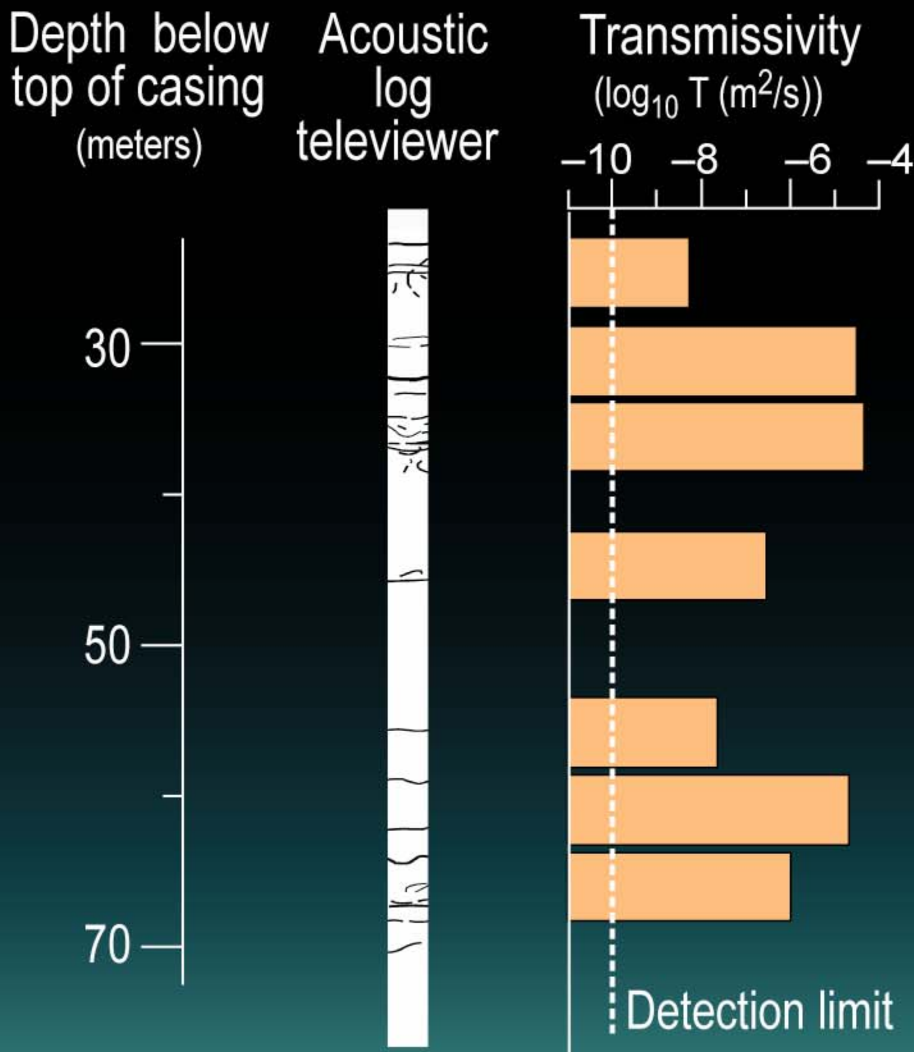
Road cut near
Mirror Lake watershed,
New Hampshire

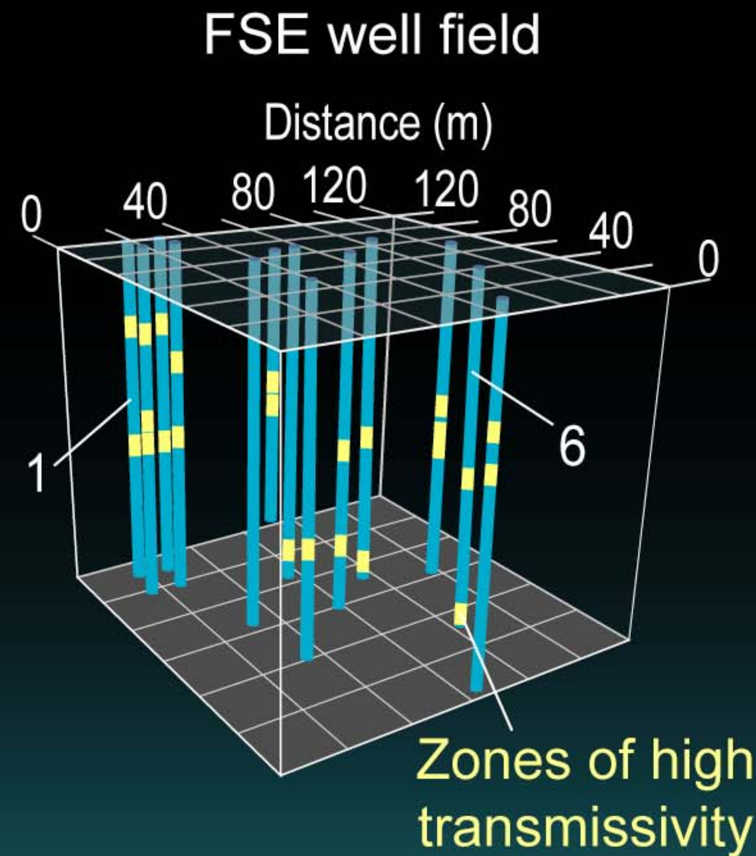


Shapiro and Hsieh, 1998

USGS

Estimating hydraulic properties over 10s of meters





Shapiro and Hsieh, 1996
Hsieh et al, 1999

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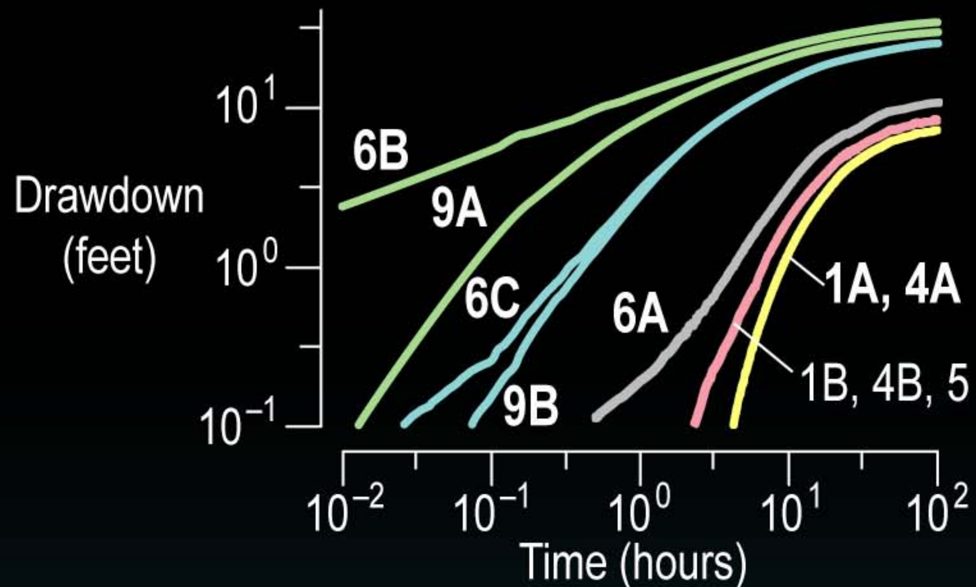
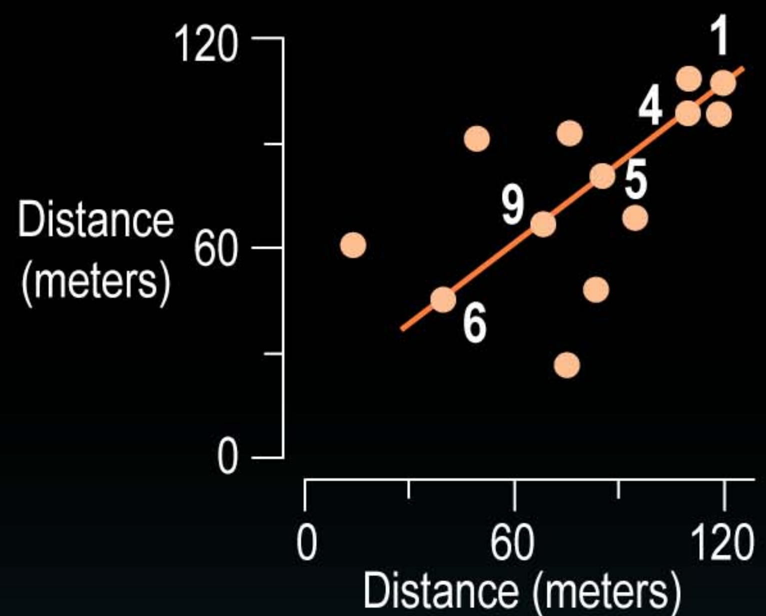
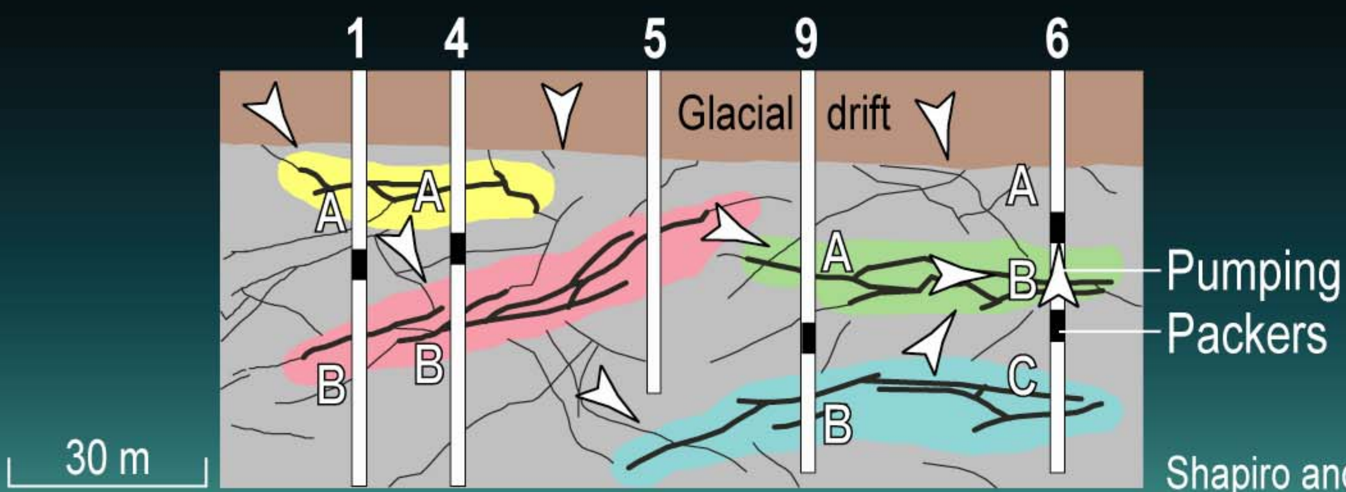
Hydraulic testing over tens of meters







Shapiro and Hsieh, 1996
Hsieh et al, 1999

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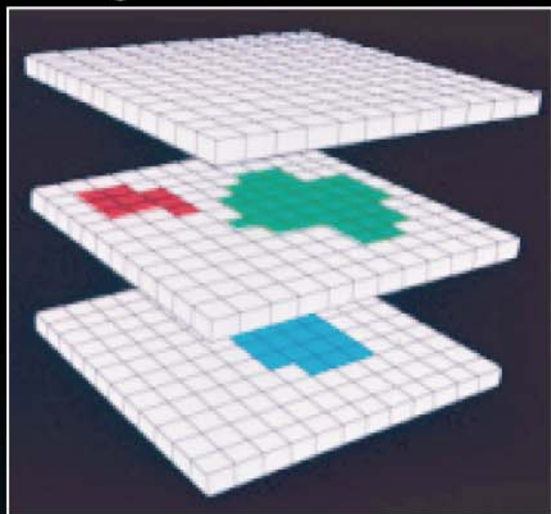
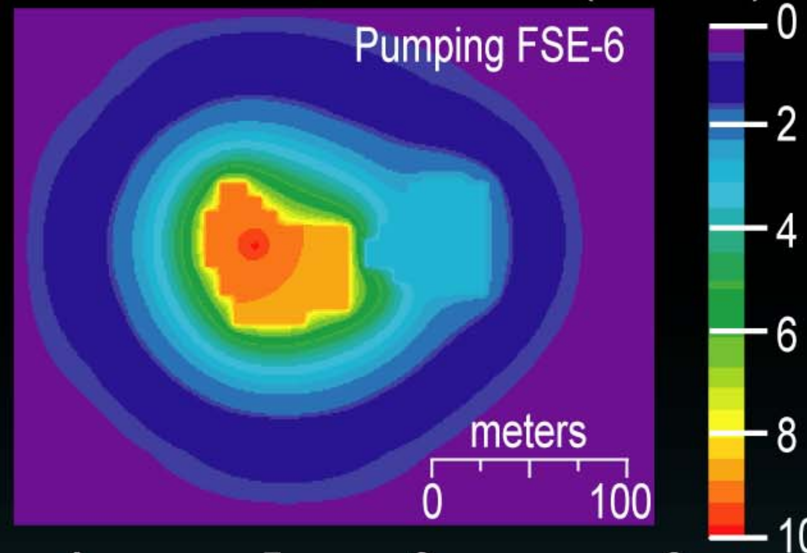
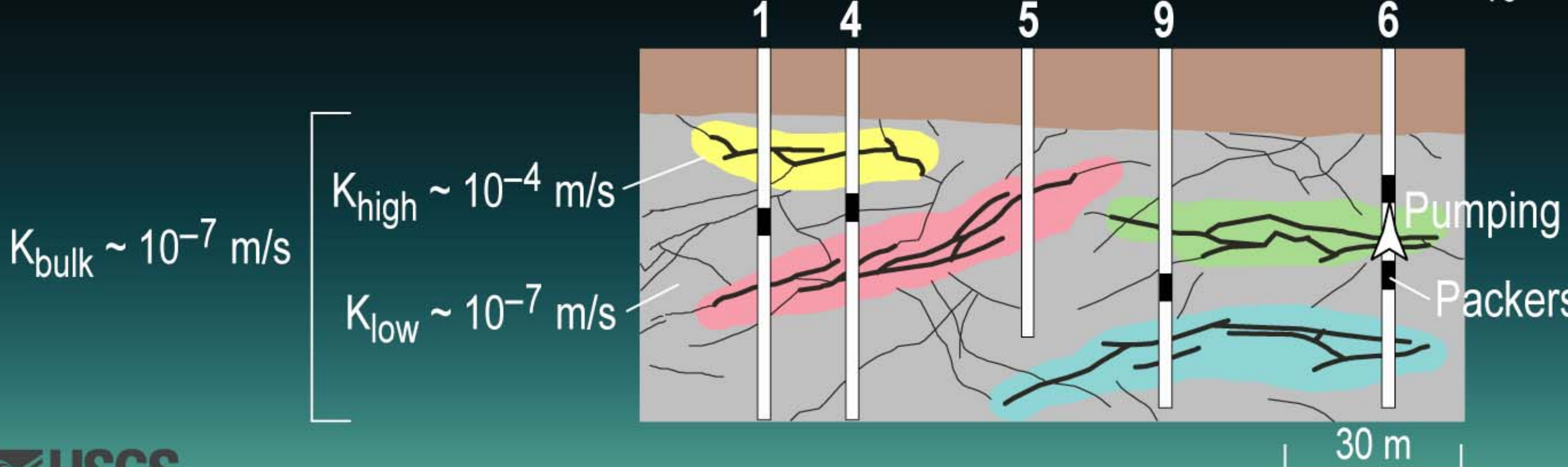
Hydraulic testing over tens of meters

Finite-difference model
for ground-water flow

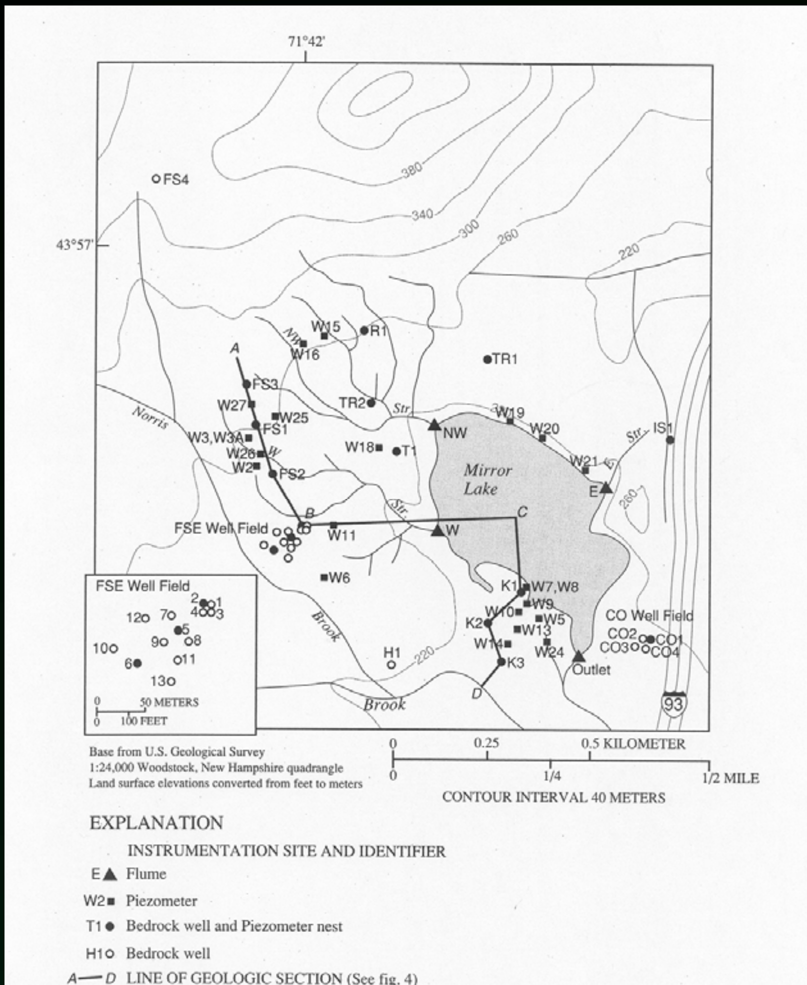


Simulated drawdown (meters)

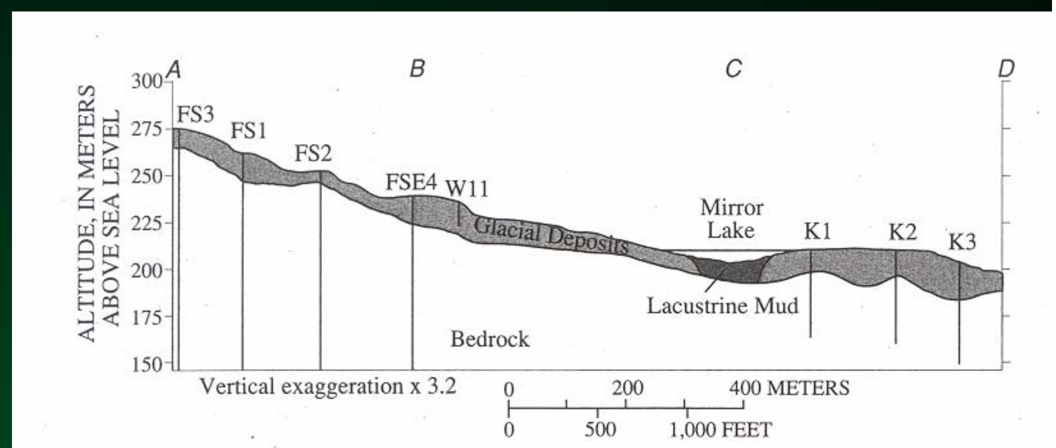




Regional Ground-Water Flow



General geologic framework



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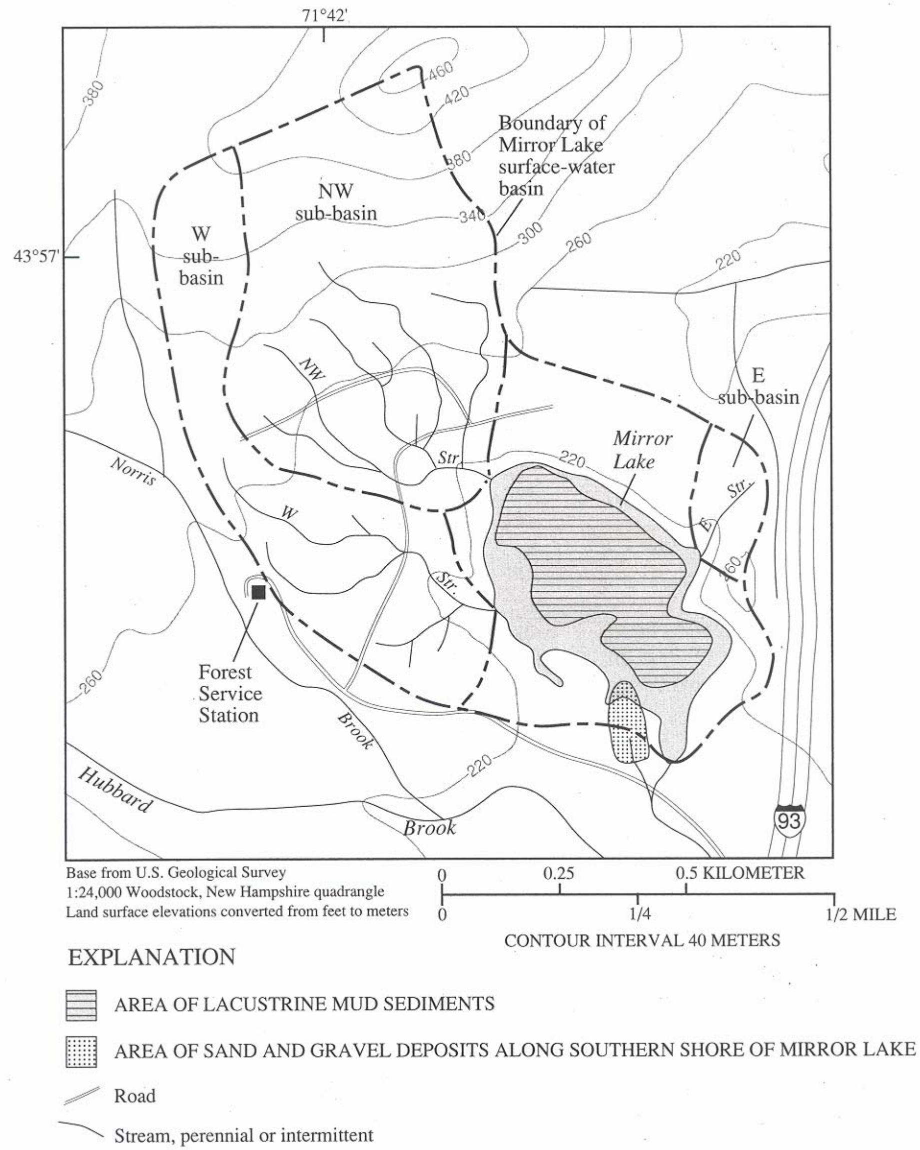
Regional Ground-Water Flow

Base flow in streams

[Streamflow and baseflow in cubic meters per year]

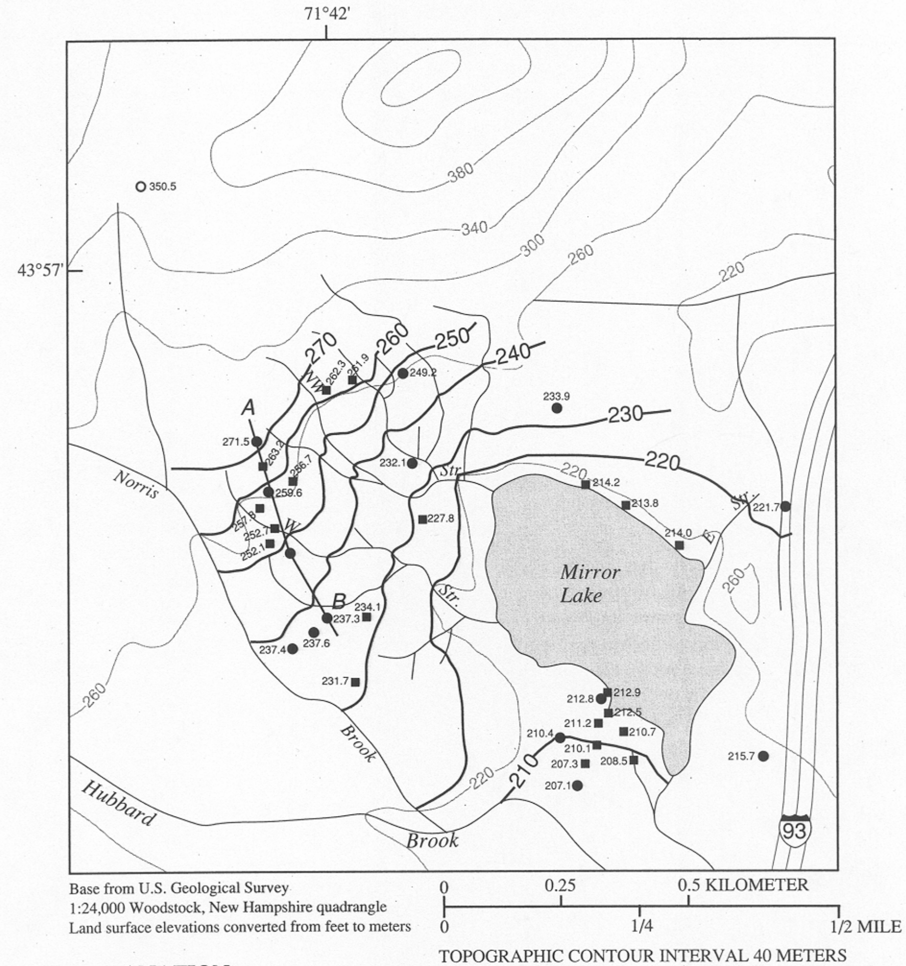
Stream	Long-term average streamflow	Long-term average baseflow[1]
W	157,000	63,000
NW	249,000	100,000
E	12,000	5,000
Total	418,000	168,000

[1]Estimated as 40 percent of streamflow.



Regional Ground-Water Flow

Water table elevation



EXPLANATION

211.2 ■ PIEZOMETER

237.4 ● BEDROCK WELL AND PIEZOMETER NEST

350.5 ○ BEDROCK WELL FS4

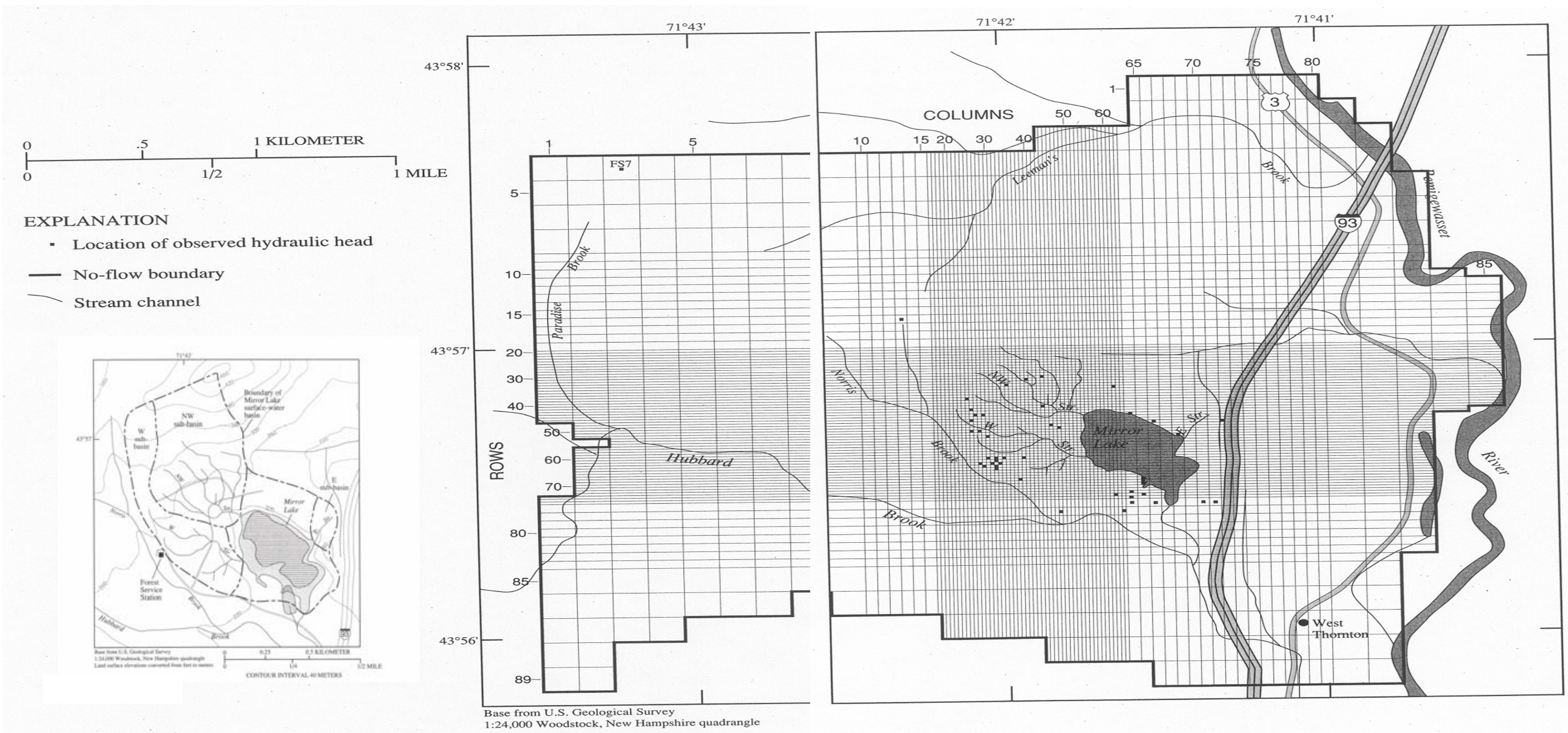
Number adjacent to symbol indicates long-term average altitude of water table, in meters above sea level.

—230— WATER TABLE CONTOUR-Shows long-term average altitude of water table. Contour interval 10 meters. Datum is sea level

A—B LINE OF HYDROLOGIC SECTION (See fig. 9)

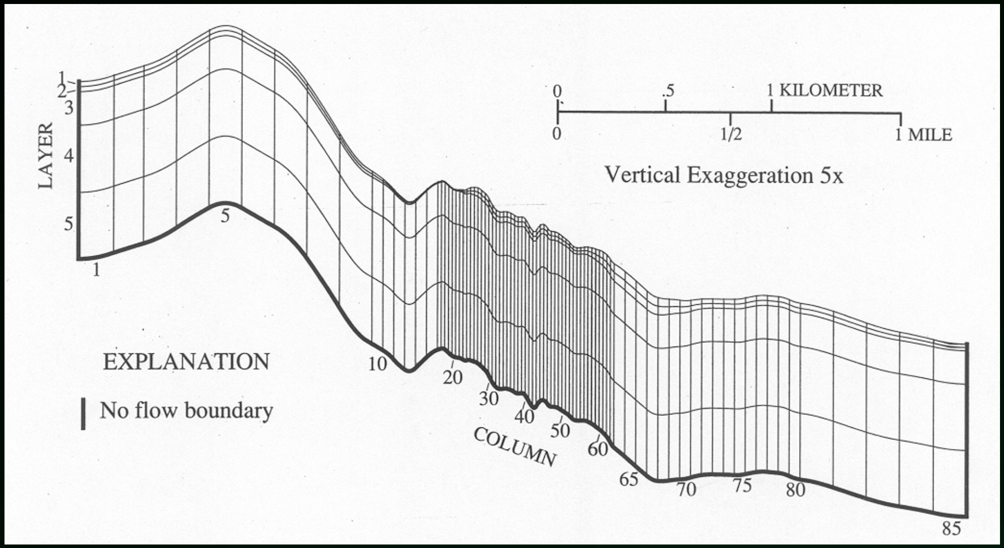
Regional Ground-Water Flow

Model domain – plan view



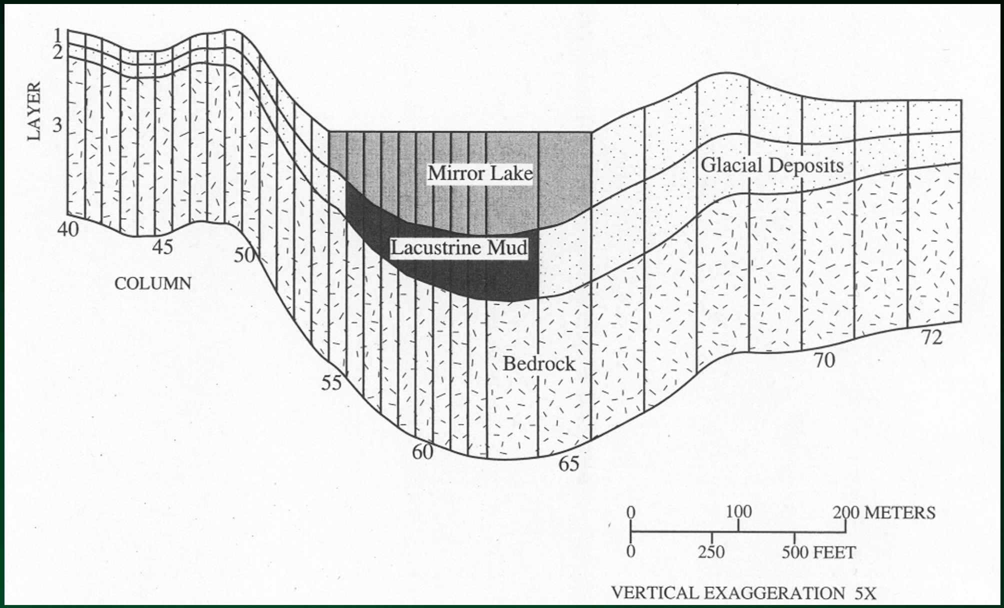
Regional Ground-Water Flow

Model domain – cross-section



- Spatial distribution of hydraulic properties of bedrock is unknown

- Assume and test several conceptual models of the distribution of hydraulic conductivity



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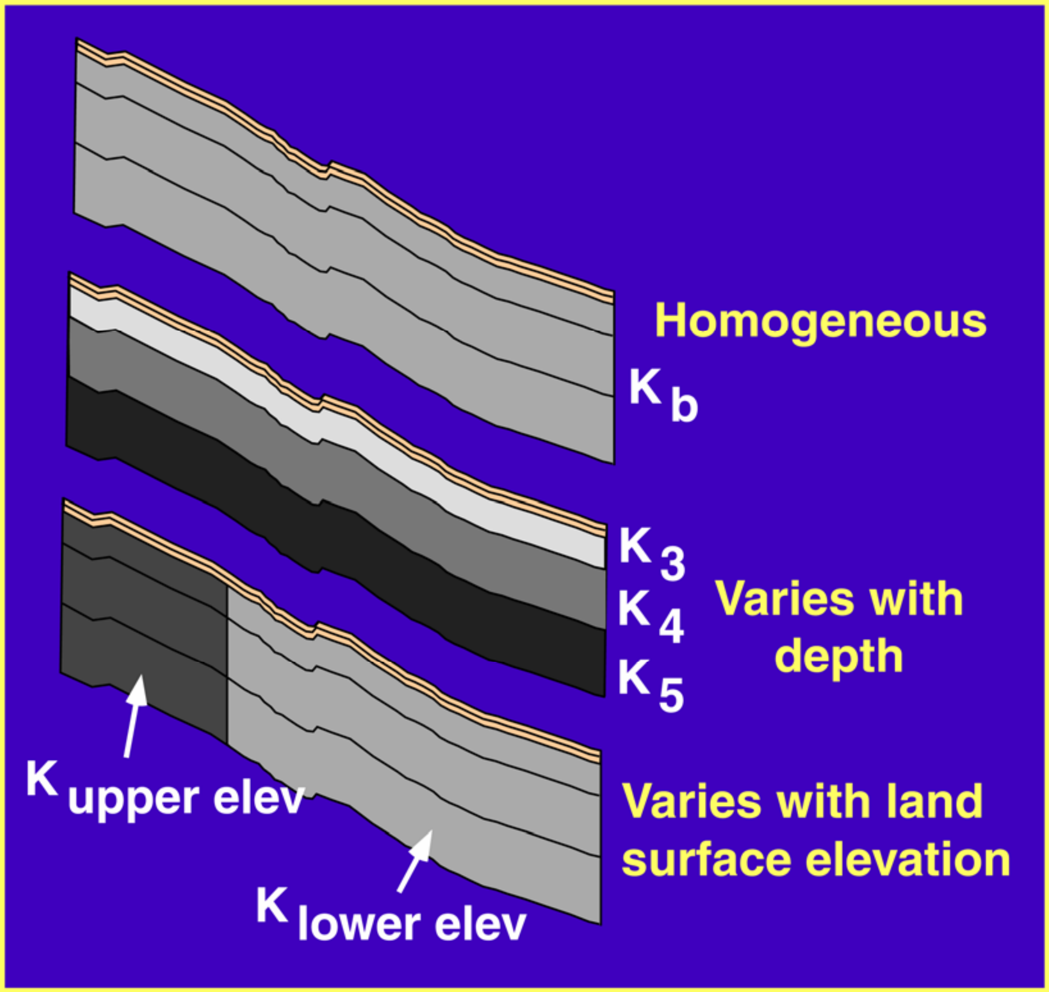
Test Different Representations of Bedrock Hydraulic Conductivity

1.

2.

3.



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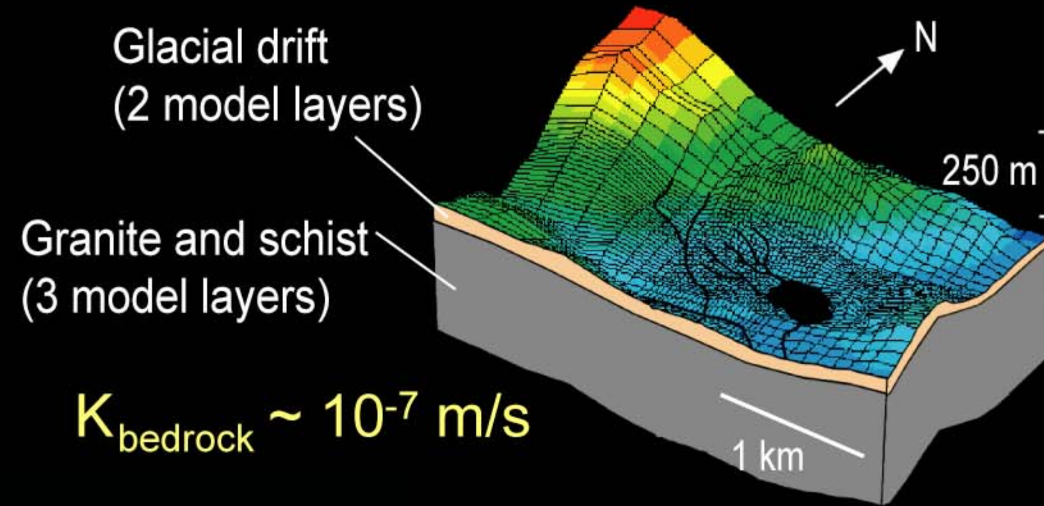
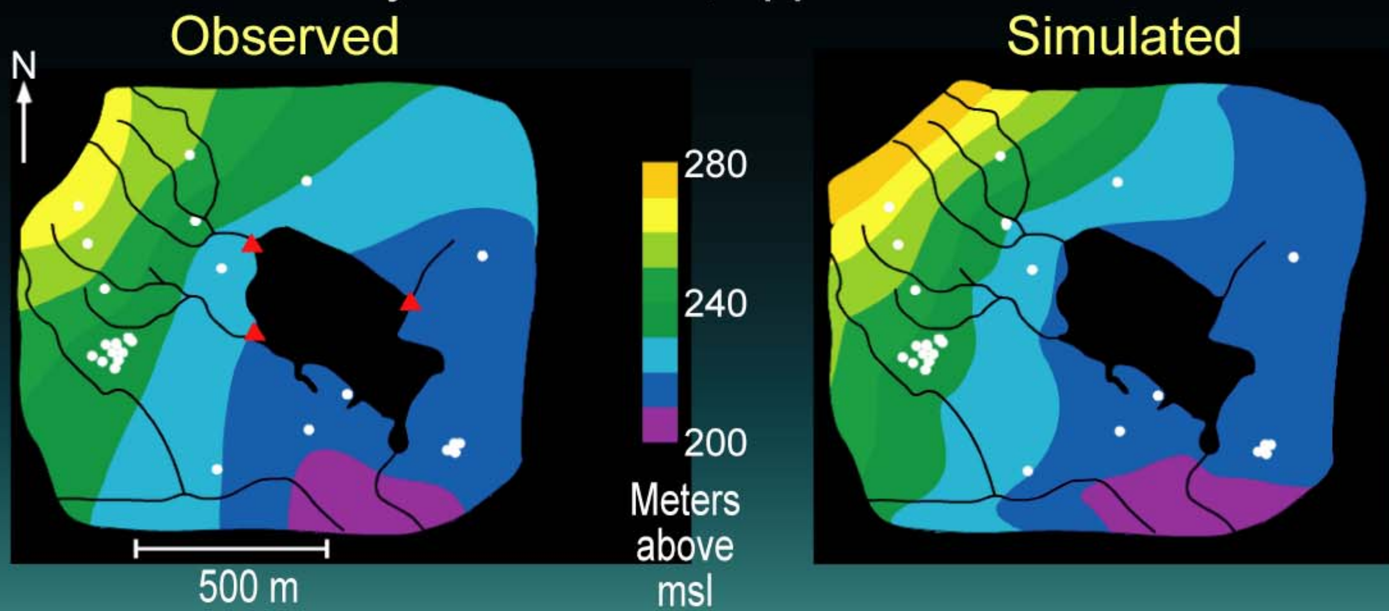
Ground-water flow over kilometers



$K_{bedrock} \sim 10^{-7}$ m/s

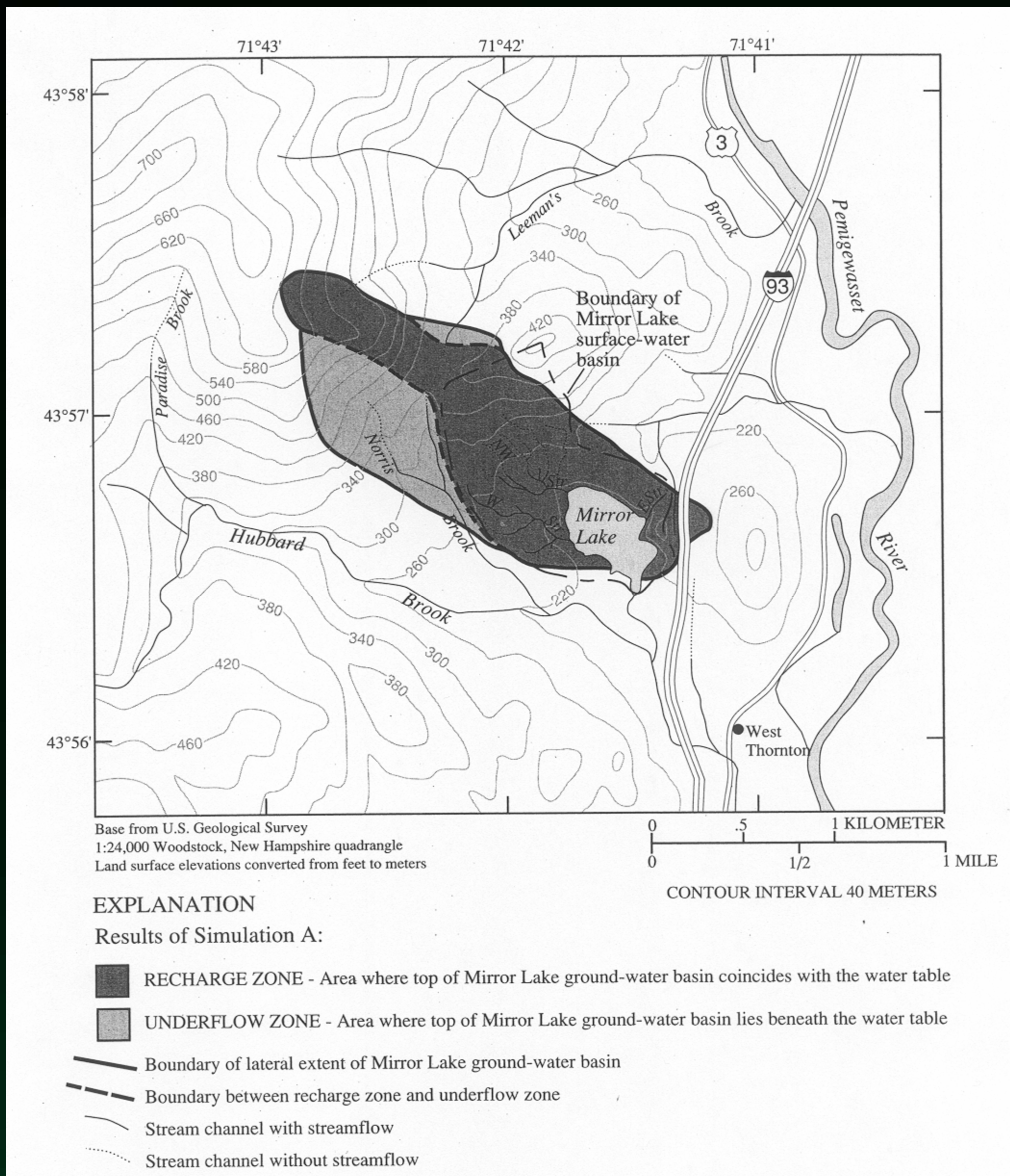
Hydraulic head, upper bedrock

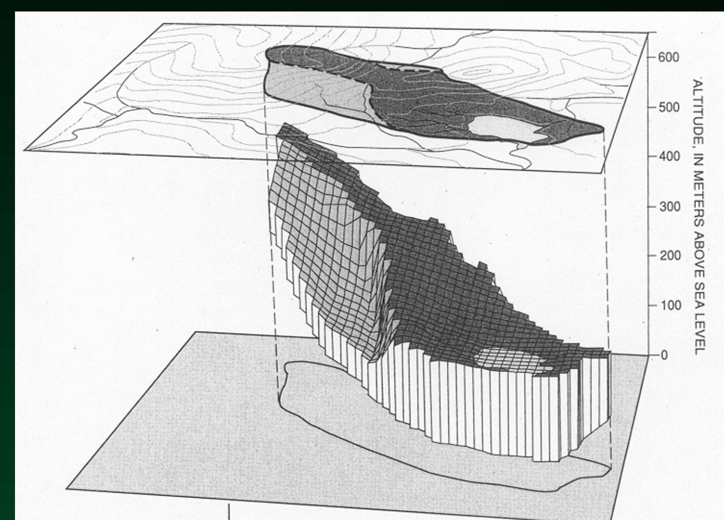


Tiedeman et al., 1997

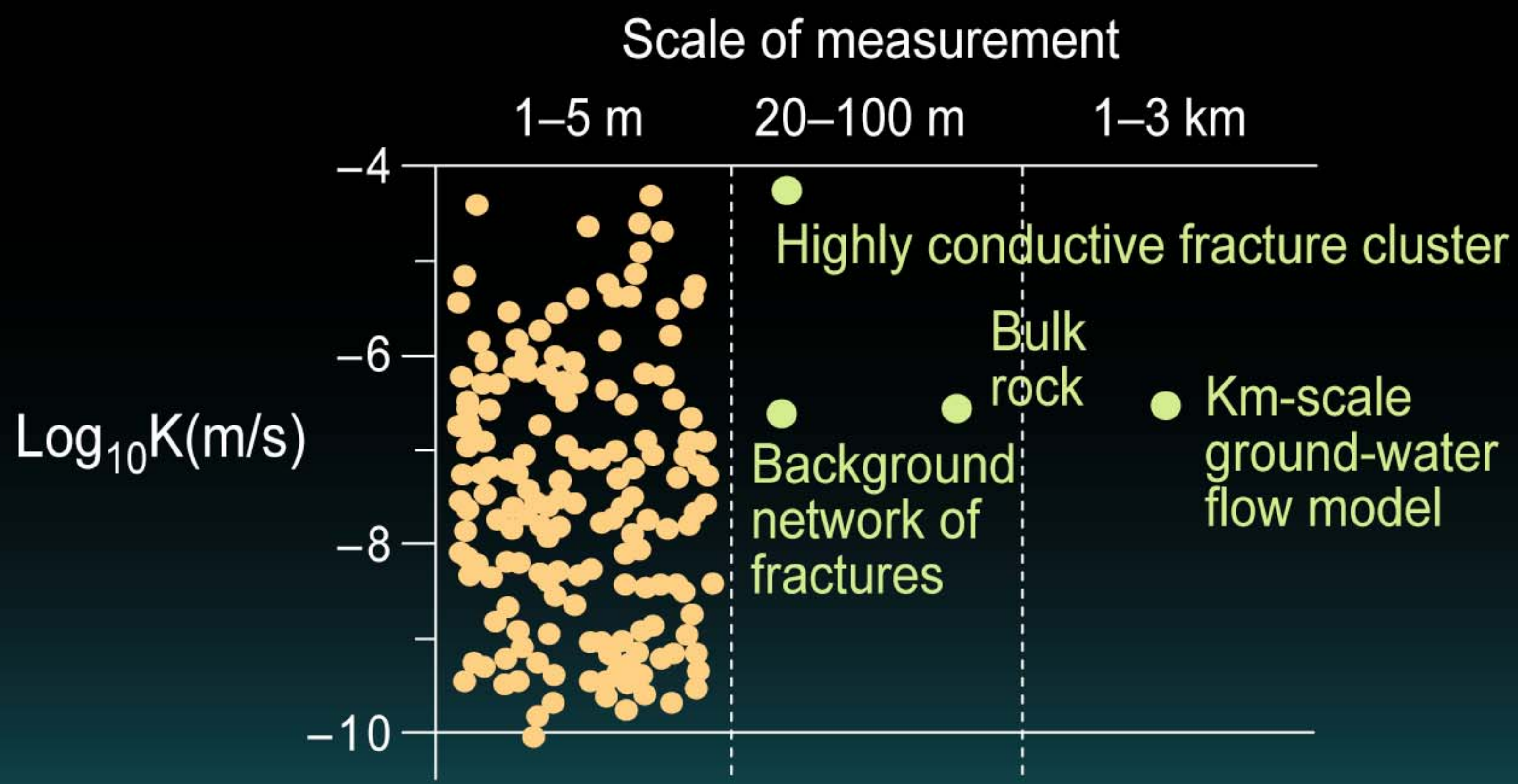
USGS

Model results





Hydraulic conductivity
Results from the Mirror Lake research site



Hsieh, 1998

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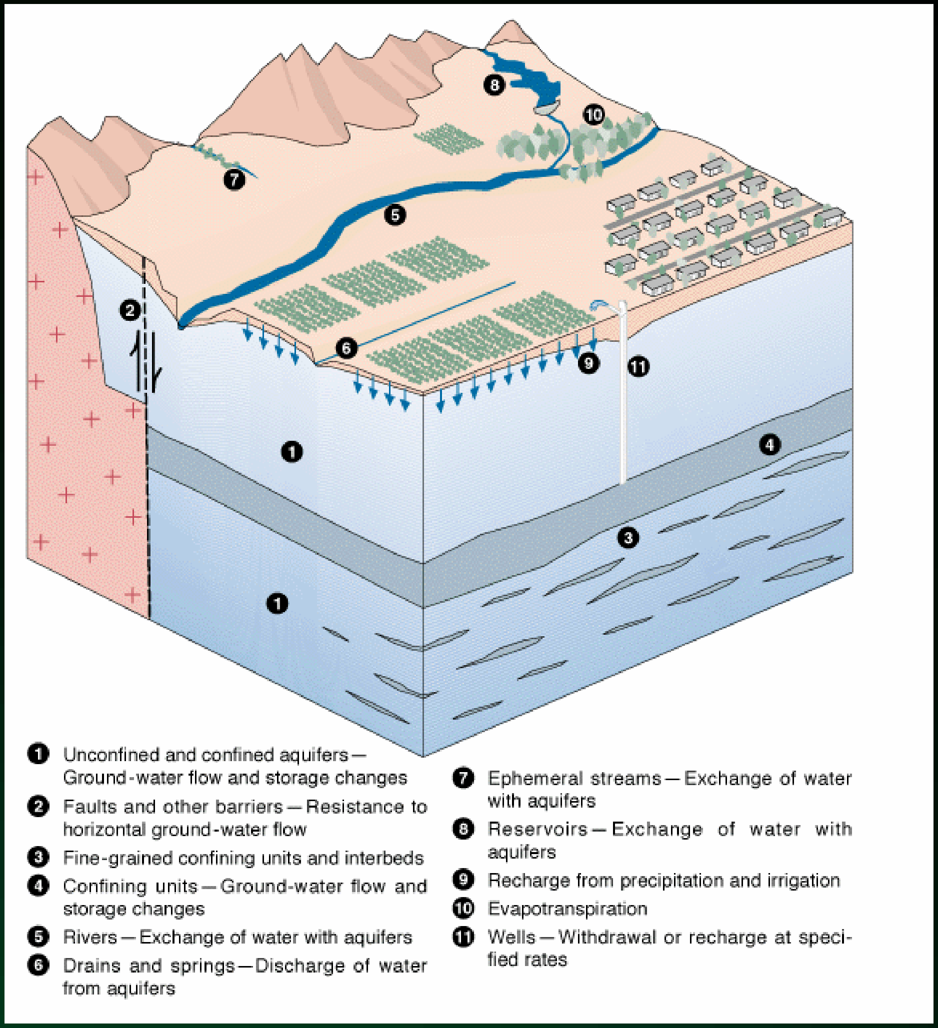
Hydrogeologic conceptual model:

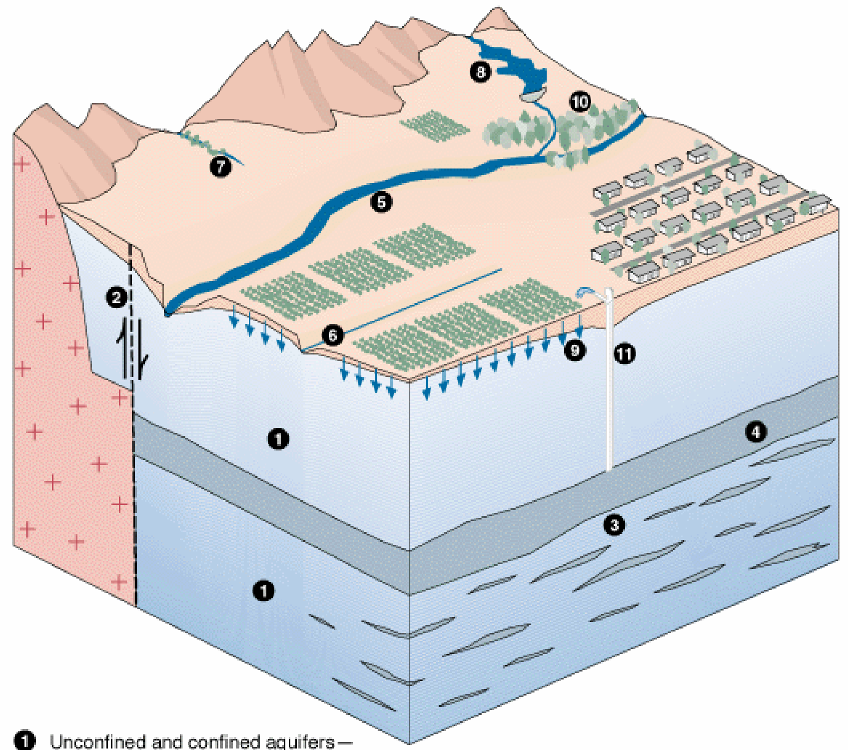
Combination of pictures and words that describe the geologic structures, hydrologeologic boundaries, and the hydrologic, meteorological, and geochemical conditions that affect the movement of ground water and chemical constituents. . .



Hydrogeologic conceptual model:

Conceptual model may not be known with certainty. . .it may be a hypothesis that needs to be revised and tested through data collection and interpretive methods. . .

Does the degree of detail in the conceptual model meet project objectives ?



1. Unconfined and confined aquifers—Ground-water flow and storage changes
2. Faults and other barriers—Resistance to horizontal ground-water flow
3. Fine-grained confining units and interbeds
4. Confining units—Ground-water flow and storage changes
5. Rivers—Exchange of water with aquifers
6. Drains and springs—Discharge of water from aquifers
7. Ephemeral streams—Exchange of water with aquifers
8. Reservoirs—Exchange of water with aquifers
9. Recharge from precipitation and irrigation
10. Evapotranspiration
11. Wells—Withdrawal or recharge at specified rates

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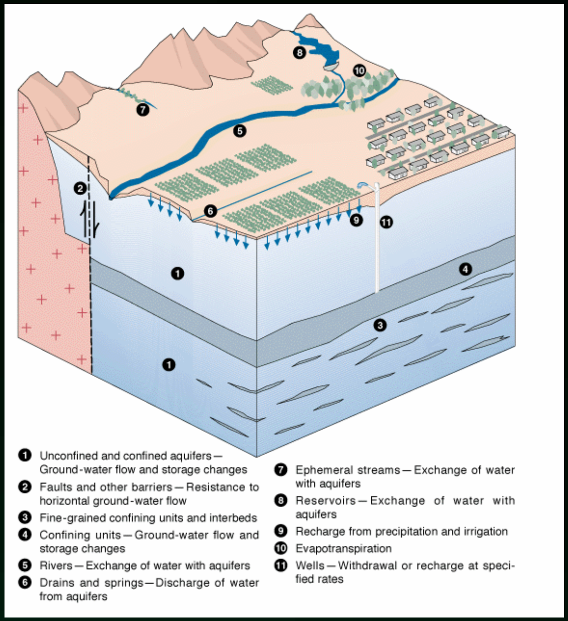
Mathematical model:

Placing the hydrogeologic conceptual model in a mathematical framework, usually in the form of “balances” of mass, momentum, and energy. . .

Includes the mathematical description of hydrogeologic boundaries and stresses. . .



$$S_s \frac{\partial h}{\partial t} - K\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}\right) = Q(x, y, z, t)$$

$$h(x = A, y = B, z = C, t) = H$$

●

●

homogeneous, isotropic, transient, etc.

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Numerical model:

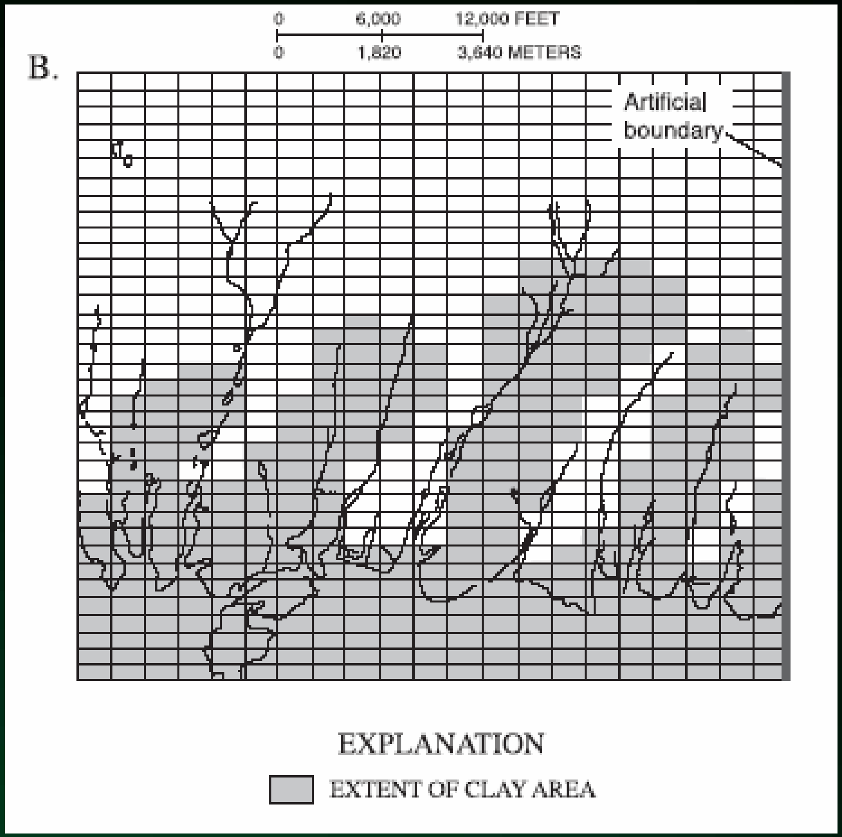
$$S_s \frac{\partial h}{\partial t} - \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = Q(x,y,z,t)$$

heterogeneous, anisotropic, etc.

Numerical models are usually developed for a very general form of the balance equations, and through the choice of aquifer parameters can be reduced to more simplified physical conditions. . .

Numerical models can handle complex aquifer geometry, complex initial and boundary conditions, and complex spatial distribution of aquifer properties. . .

Does the application of a numerical model fit project objectives ?



$$S_{s(i,j,k)} \frac{\left(h_{i,j,k}^{t+\Delta t} - h_{i,j,k}^{t}\right)}{\Delta t}$$

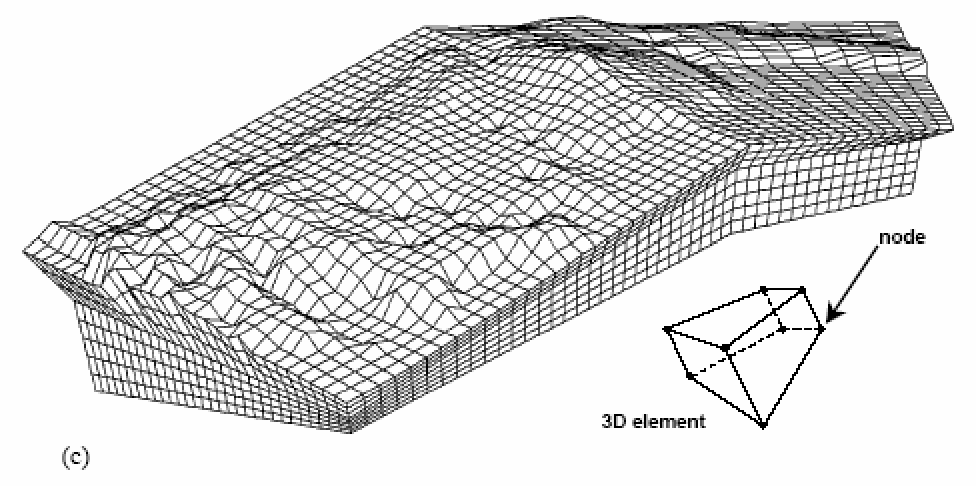
$$-\frac{1}{\Delta x}\left(K_{i+\frac{1}{2}\Delta x, j,k} \frac{h_{i+1,j,k}^{t+\Delta t} - h_{i,j,k}^{t+\Delta t}}{\Delta x} - \ldots\right) - \ldots = Q_{i,j,k}^{t+\Delta t}$$

Numerical model:

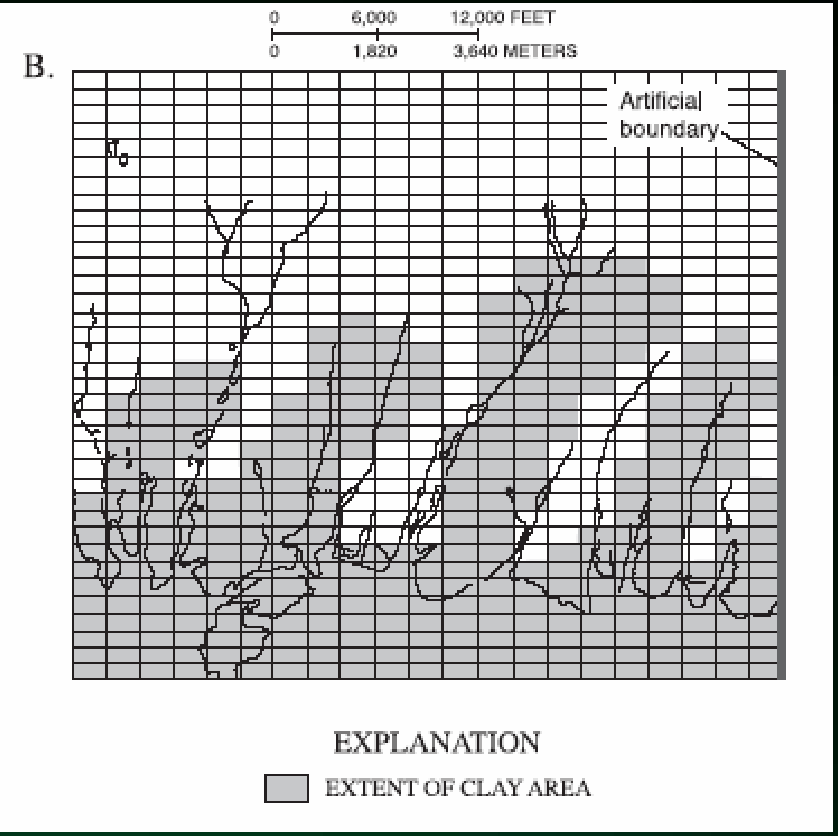
$$S_s \frac{\partial h}{\partial t} - \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = Q(x, y, z, t)$$

heterogeneous, anisotropic, etc.

USGS MODFLOW (finite-Difference algorithm) and USGS SUTRA (finite-element algorithm) are examples of numerical models. . .



Finite-Element Mesh



Finite-Difference Grid

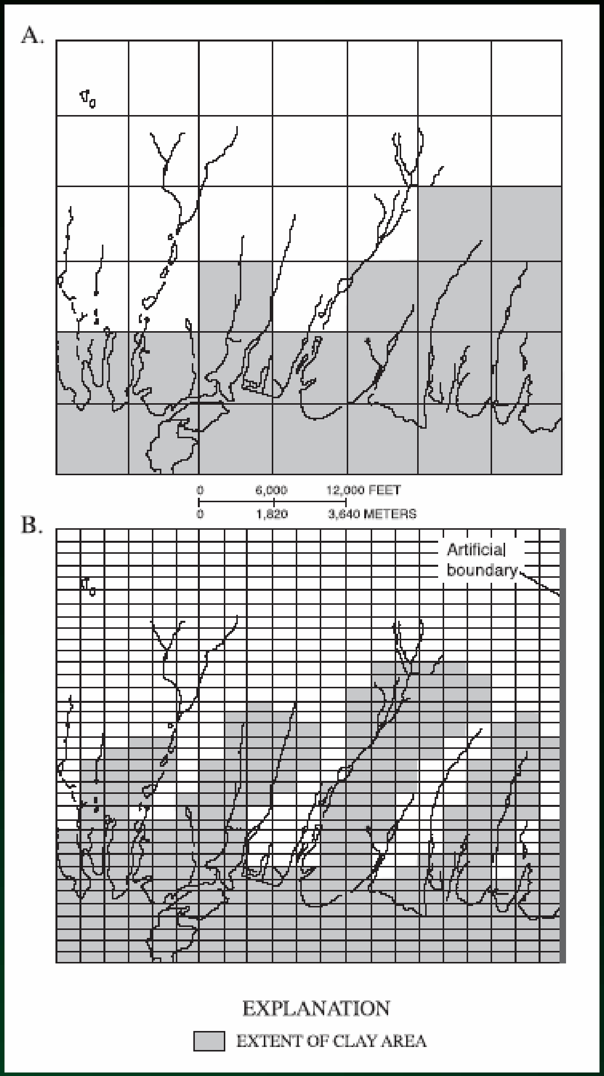
USGS

Project Objectives:

Are the objectives of the study clearly stated?

Will the mathematical model capture the important physical/chemical/biological processes needed to describe the ground-water system and address project objectives?

Ground-water modeling is a component in an iterative process to understand hydrogeology and project objectives. . .



USGS

THAT'S LIFE *By* Mike Twohy

"You can do a lot with computer models, but at some point you have to use real animals."