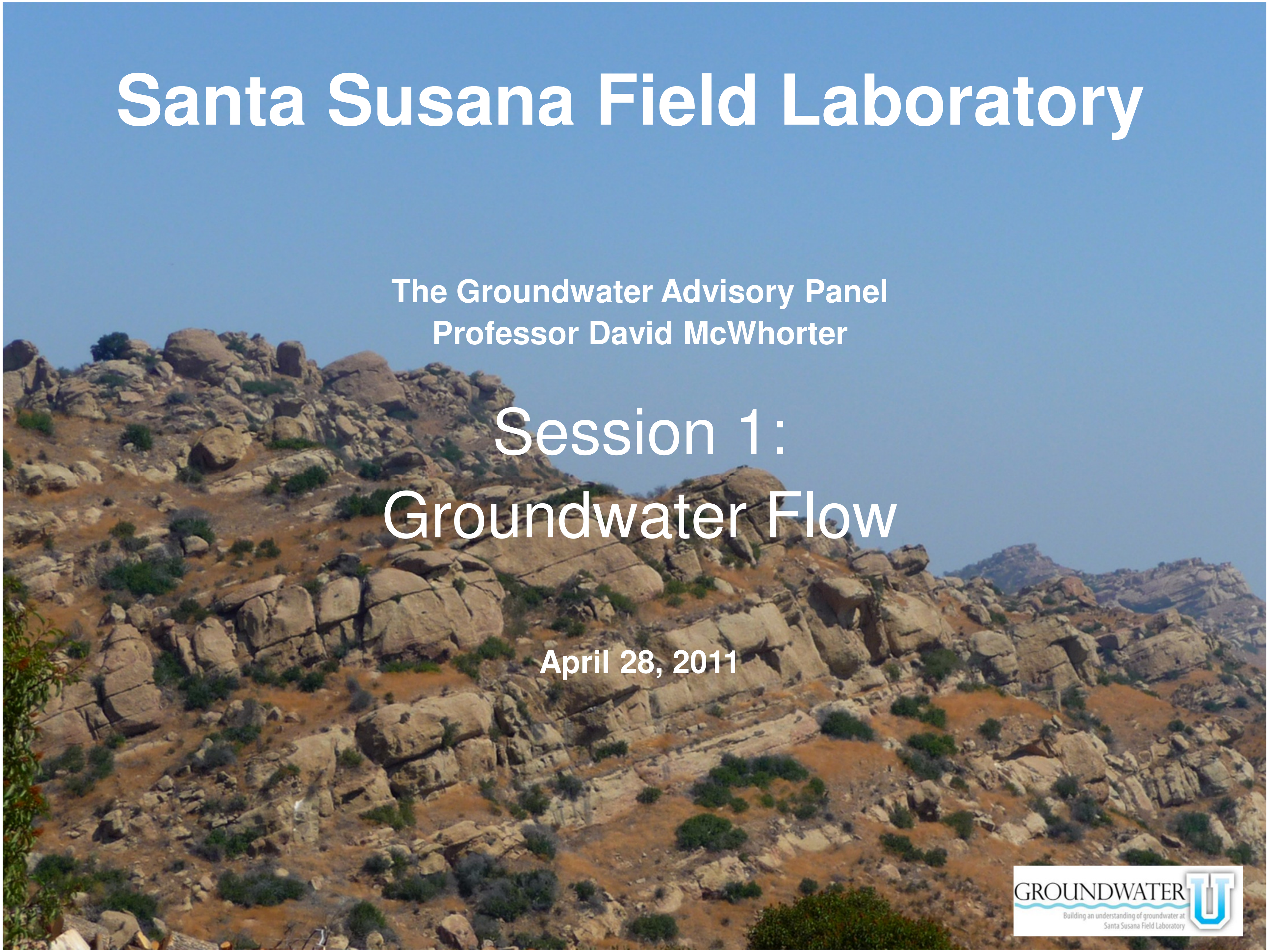


Santa Susana Field Laboratory

The Groundwater Advisory Panel

Professor David McWhorter

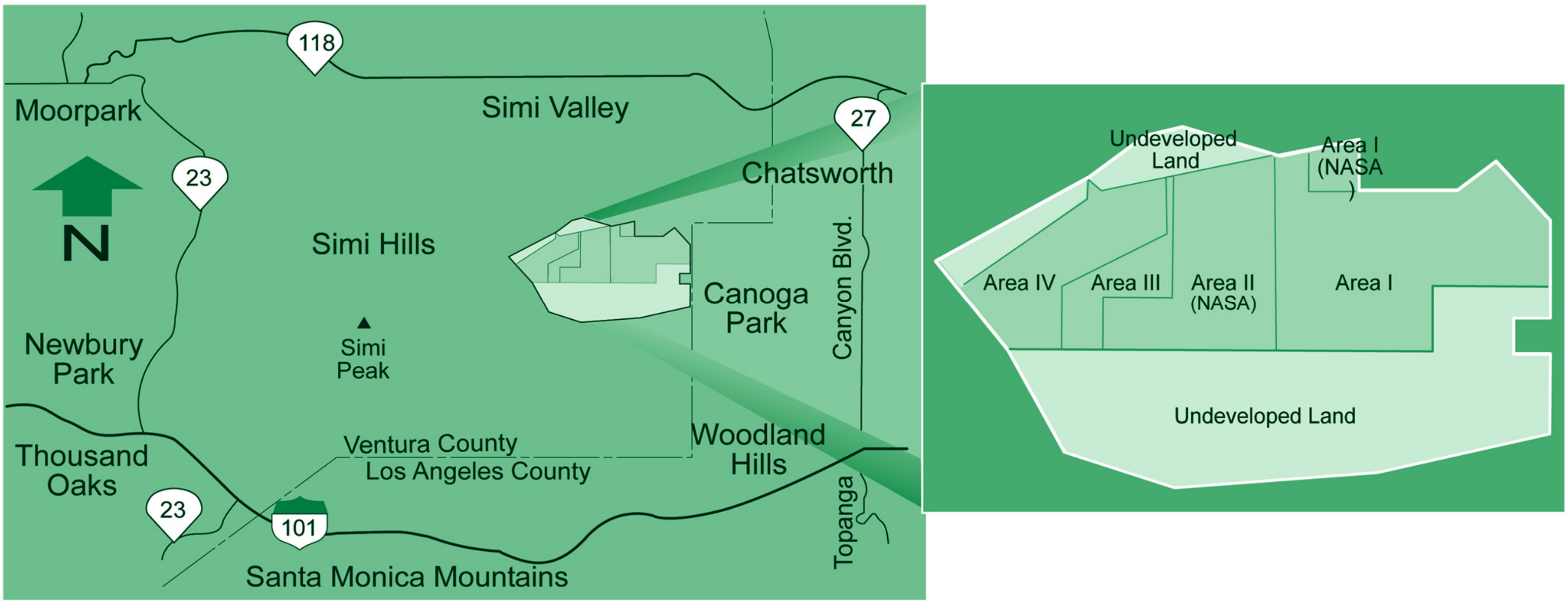
Session 1:
Groundwater Flow

April 28, 2011

GROUNDWATER U
Building an understanding of groundwater at Santa Susana Field Laboratory

Upland Site between Communities

Overall Property is 2,850 acres 3 miles x 1.5 miles



Boeing-owned:

Area I 670 acres

Area III 114 acres

Area IV 290 acres; DOE-leased 90 acres

Undeveloped Land - Boeing-owned 1,325 acres

NASA-owned:

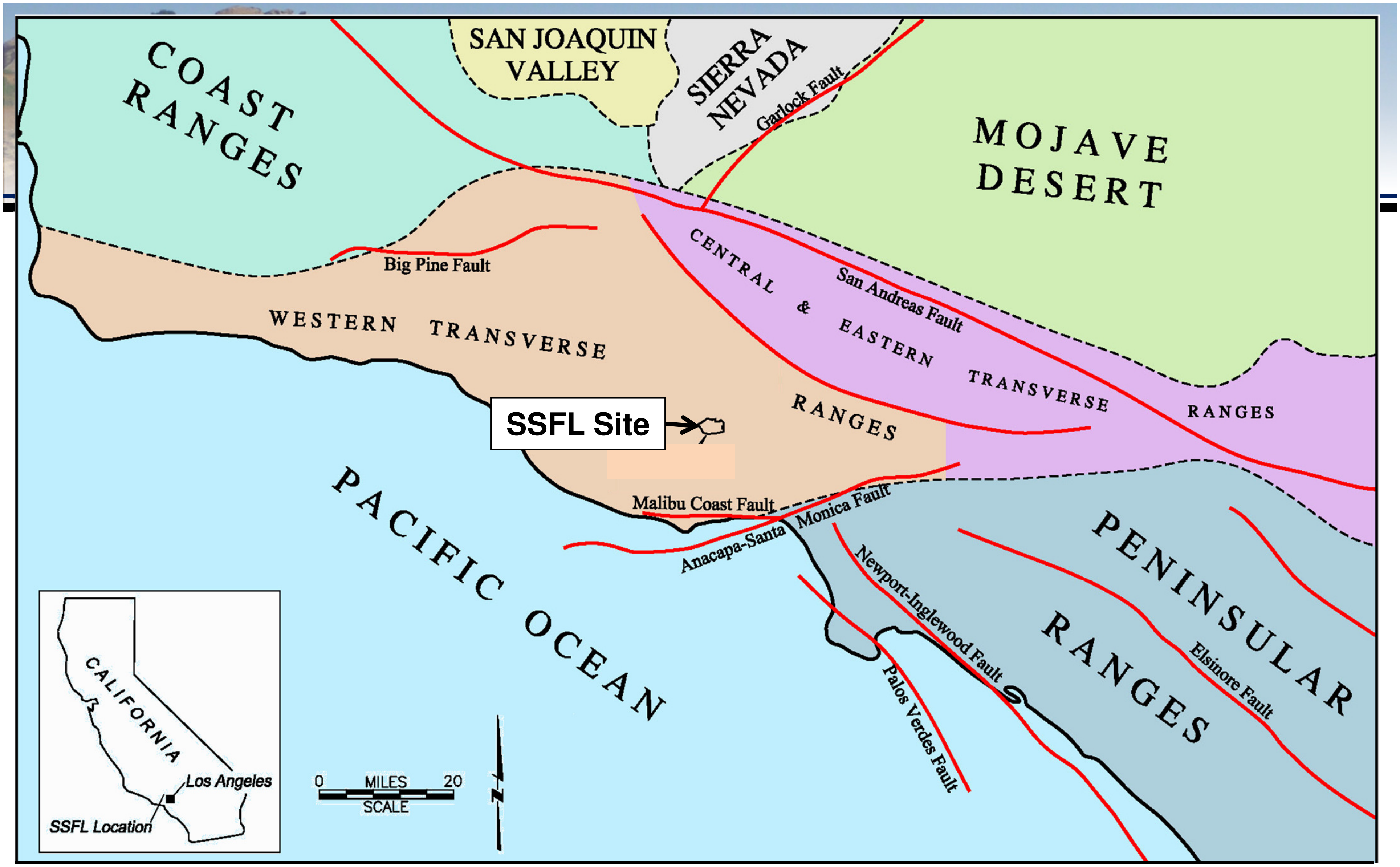
Area I: ~50 acres

Area II: 400 acres

Why this lecture?

Groundwater is a potential pathway for contaminants to reach points of exposure.

Study of groundwater flow is a prerequisite to understanding how contaminants migrate.

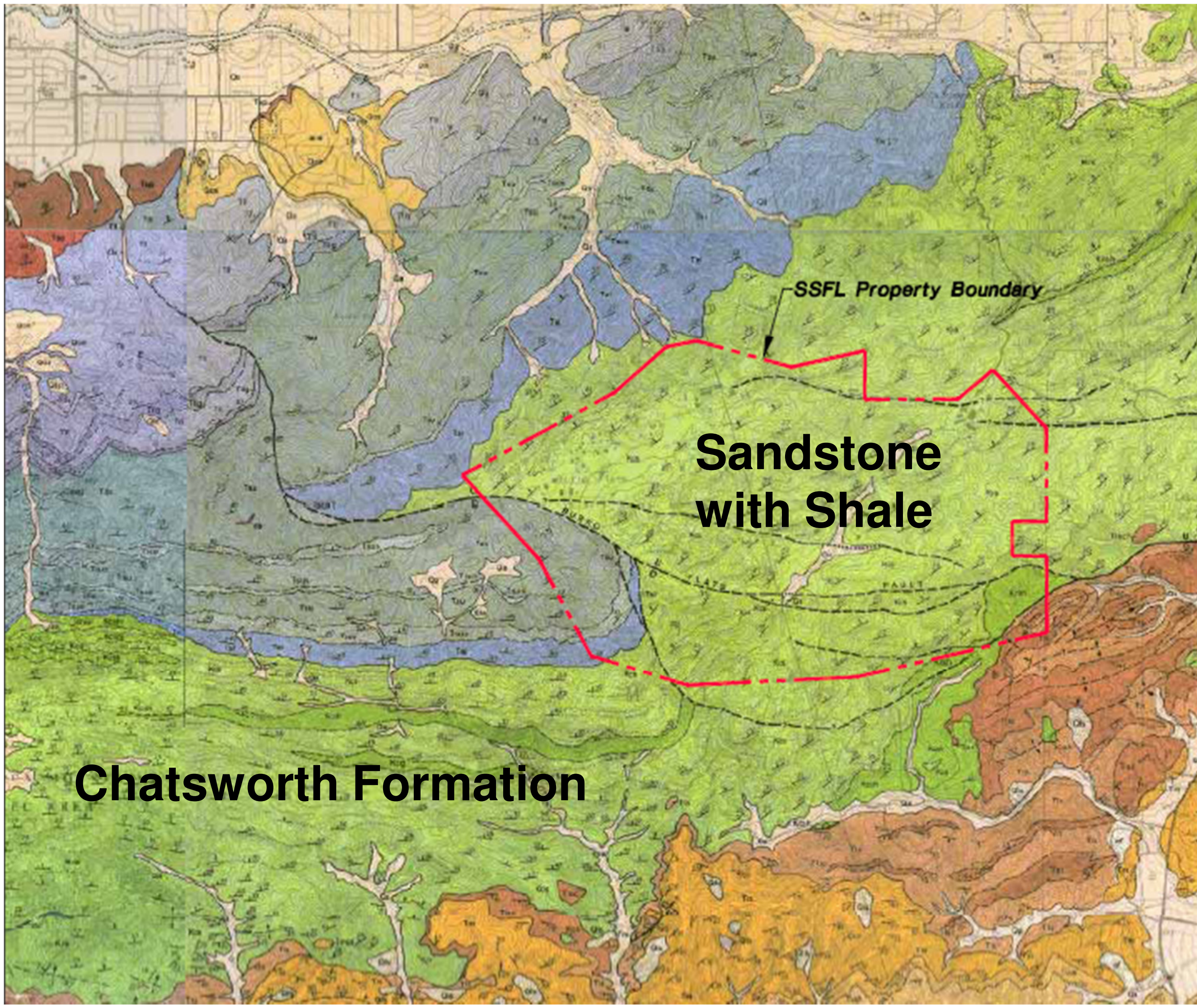


SSFL in Relation to the Physiographic Provinces of Southern California

Santa Susana Field Laboratory, Ventura County, California

Source: Yerkes and Campbell, 2005

Bedrock Geology



Simi Formation Conglomerate

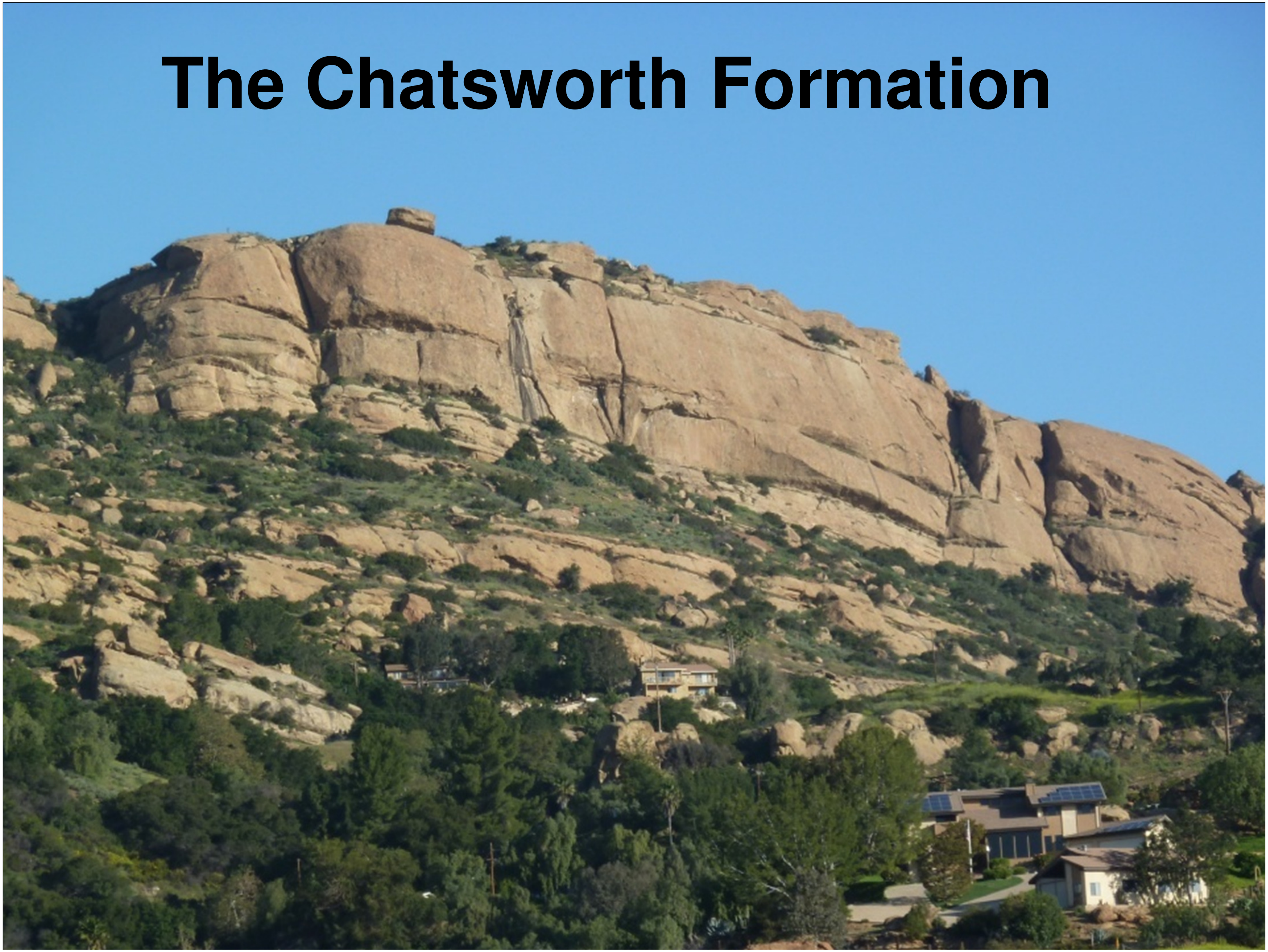
Santa Susana Formation Sandstone

Chatsworth Formation Sandstone

Monterey Formation Sandstone

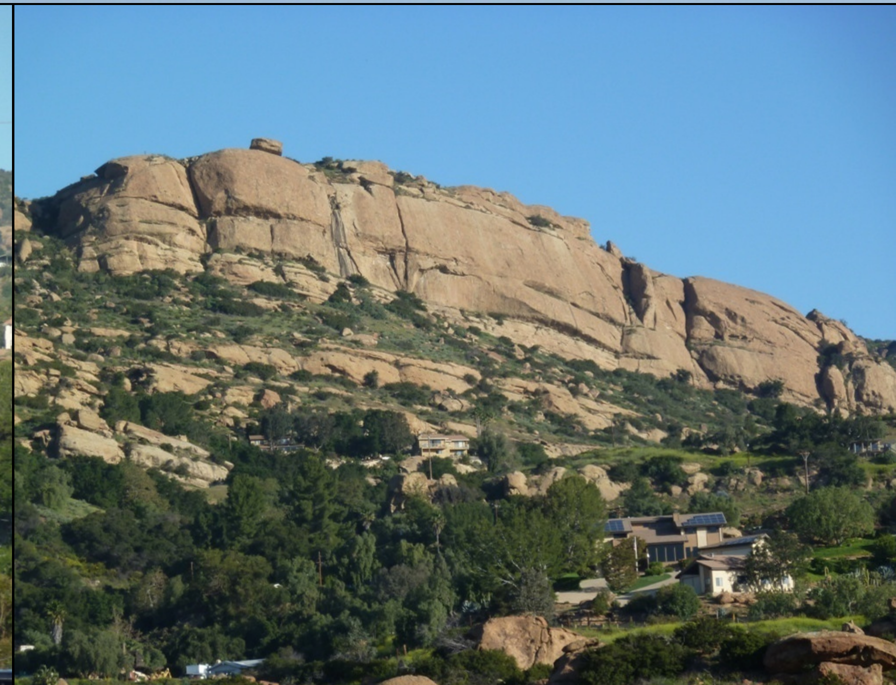
Sespe Formation Sandstone and Conglomerate

The Chatsworth Formation




HATSWORTH
LAKE

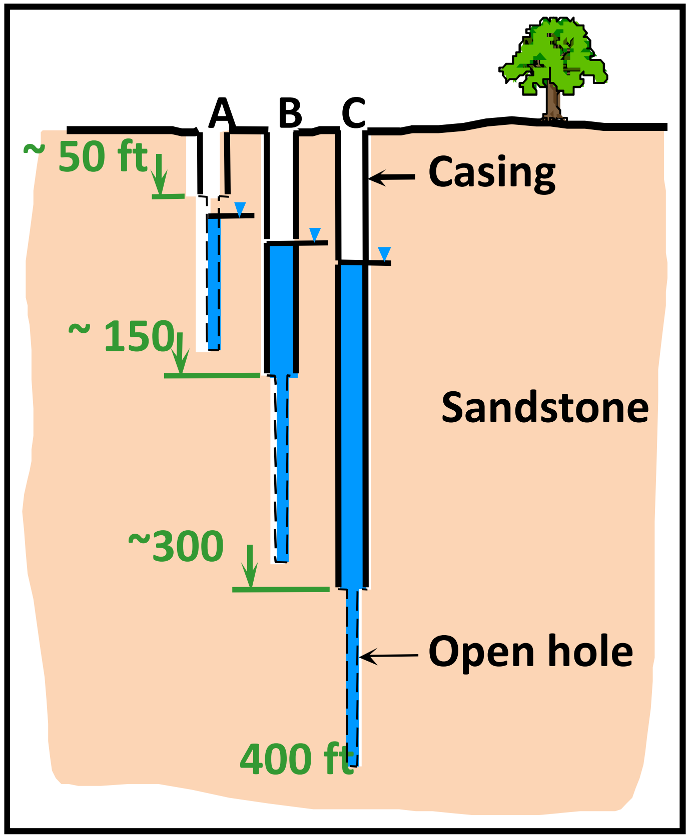

30 Degrees



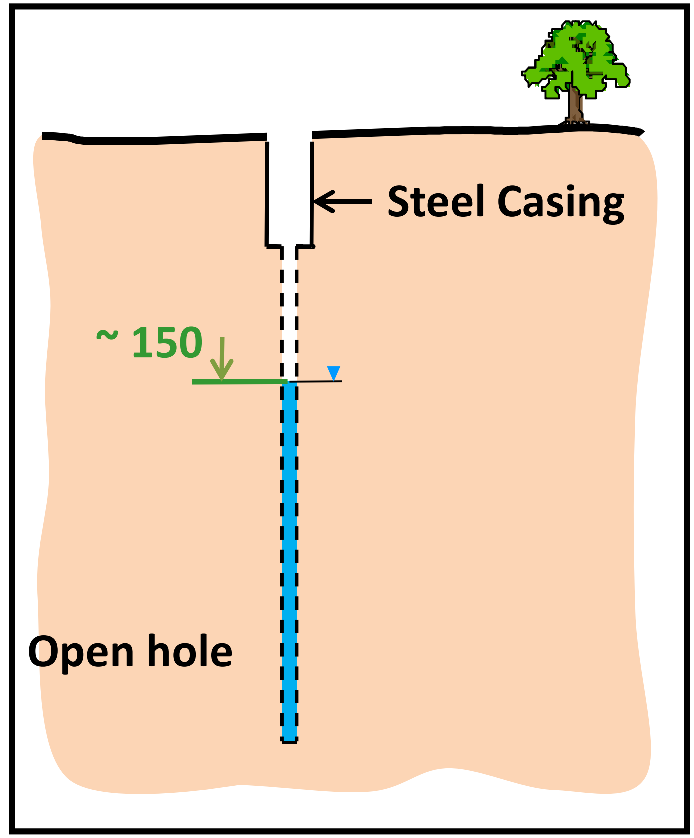

BOEING
5800 Woolsey
Canyon Road

CONVENTIONAL MONITORING WELLS

Conventional Monitoring well nest

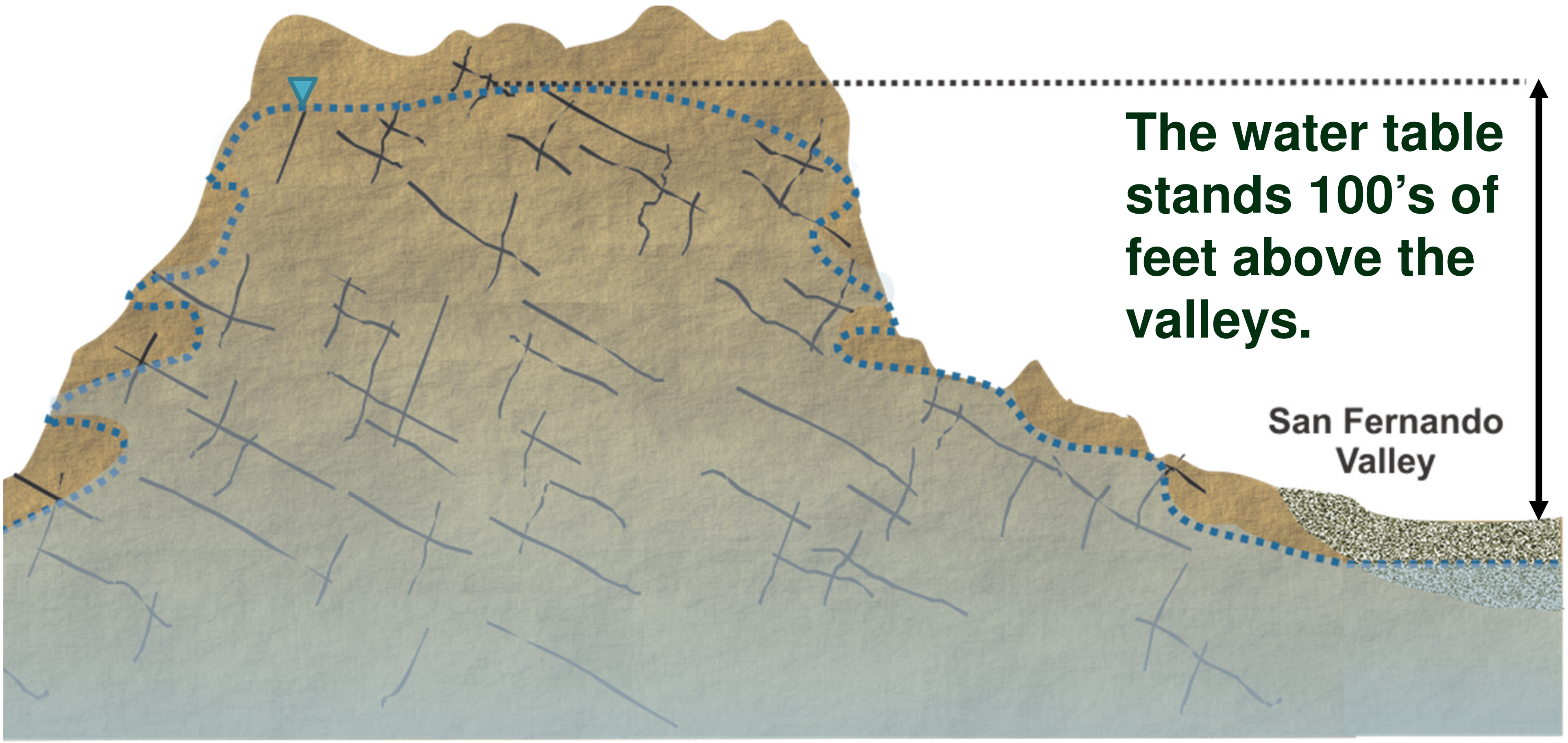


Monitoring well with Long Open Intake



Conventional Wells

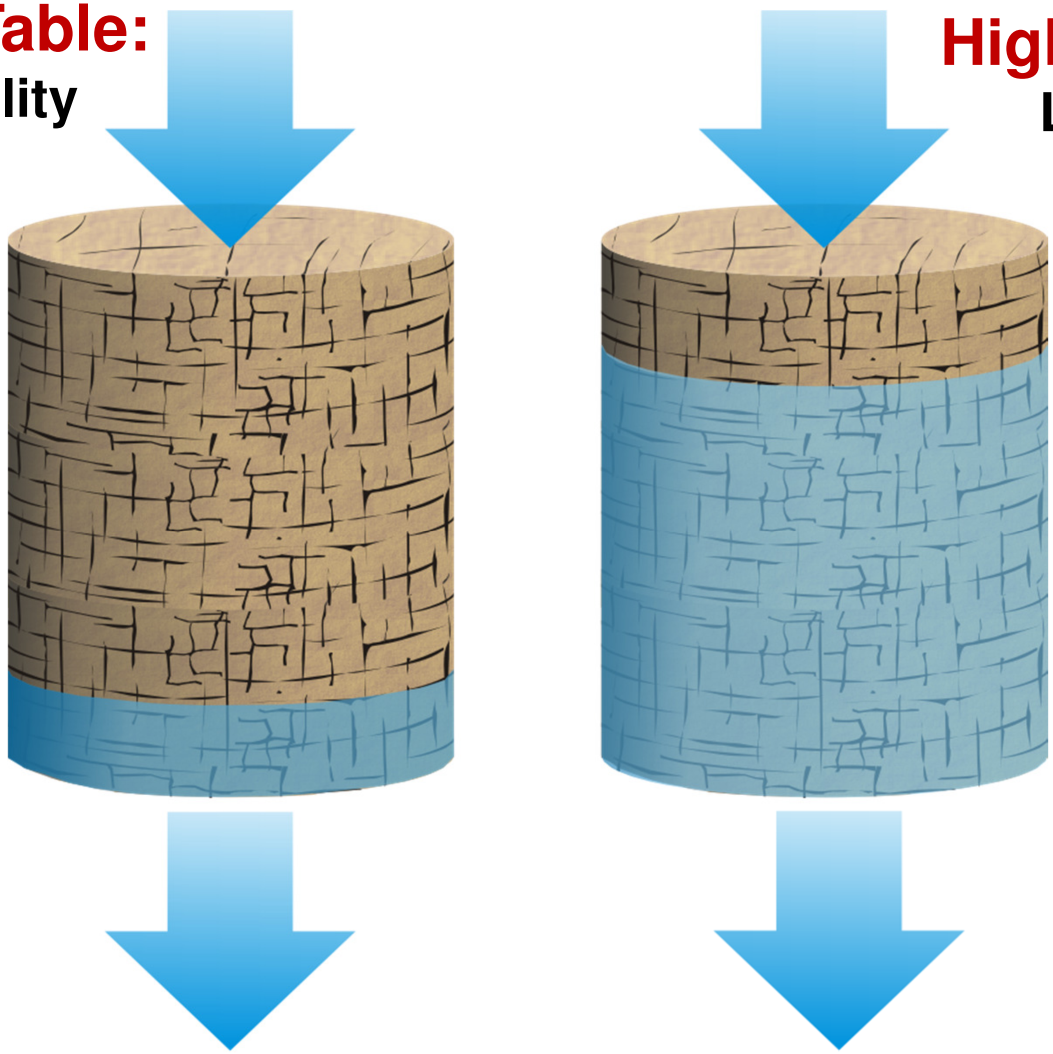
Why does the SSFL groundwater level stay high above the surrounding valleys?



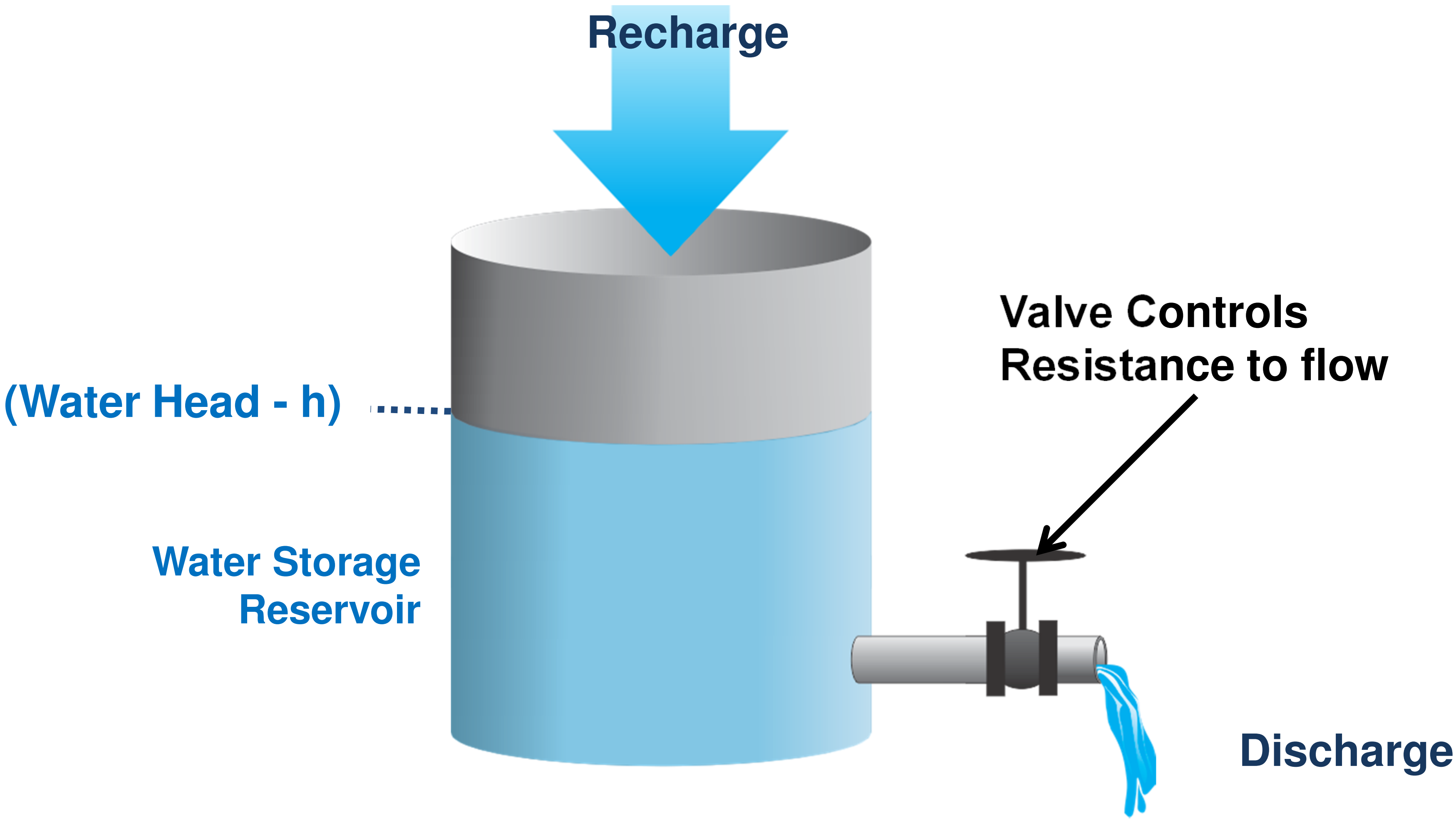
How Permeable is the Mountain?

Low Water Table:
High Permeability

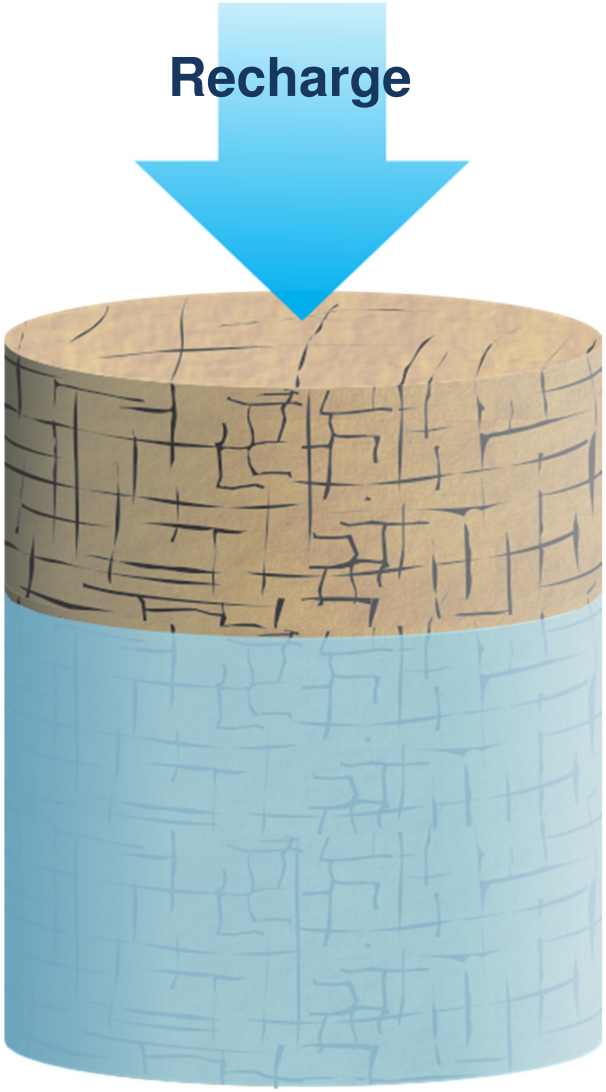
High Water Table:
Low Permeability



Resistance to Flow

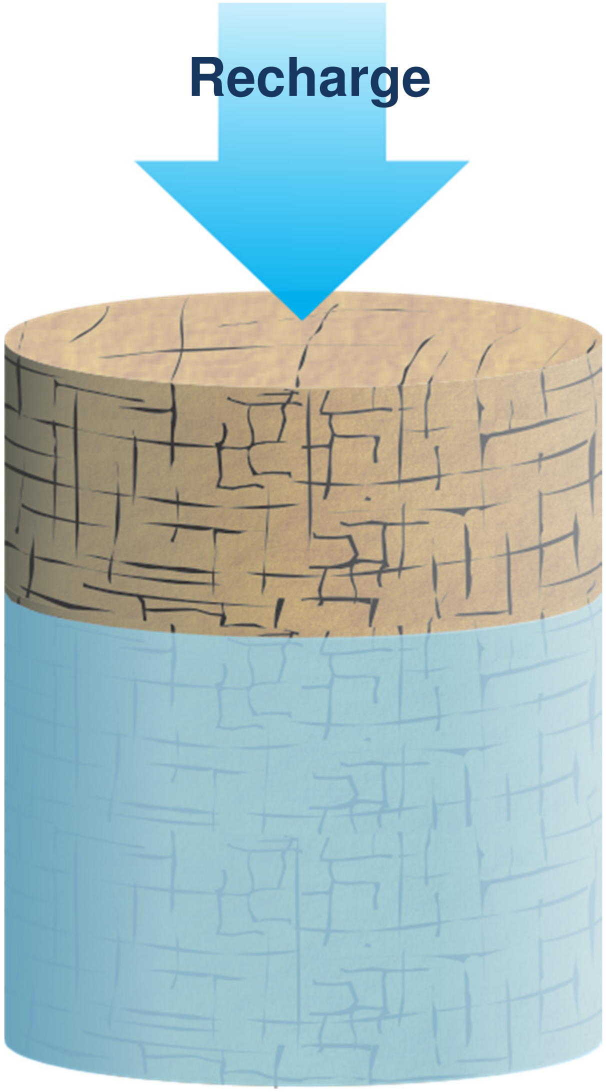


Bulk Permeability



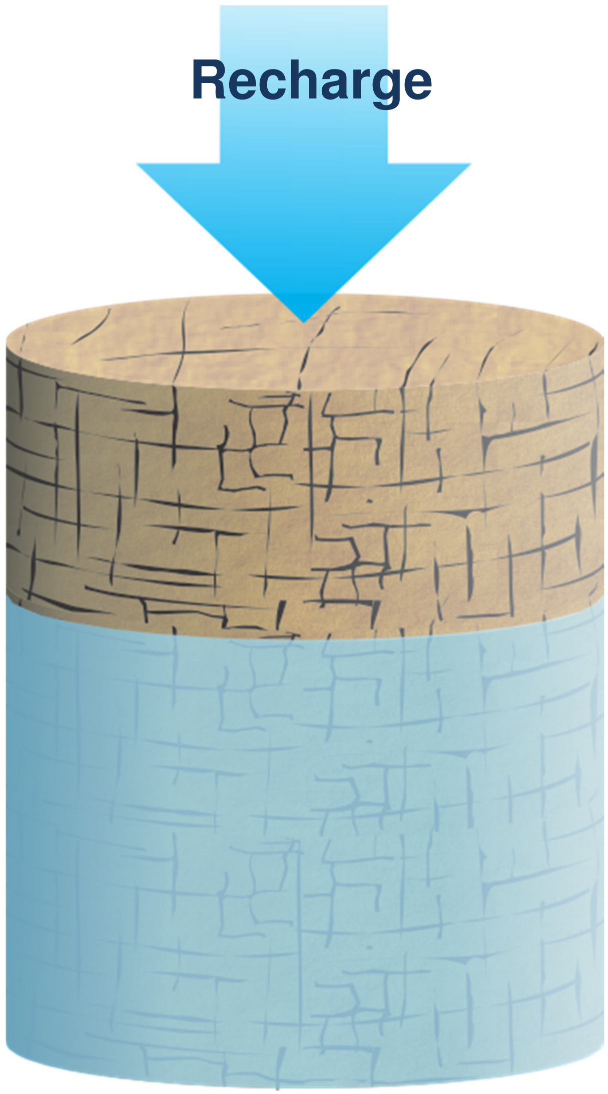
Resistance to flow - Bulk Permeability of fractured Rock

Hydraulic Conductivity = K



K is a measure of the resistance to flow of water

Hydraulic Conductivity = K

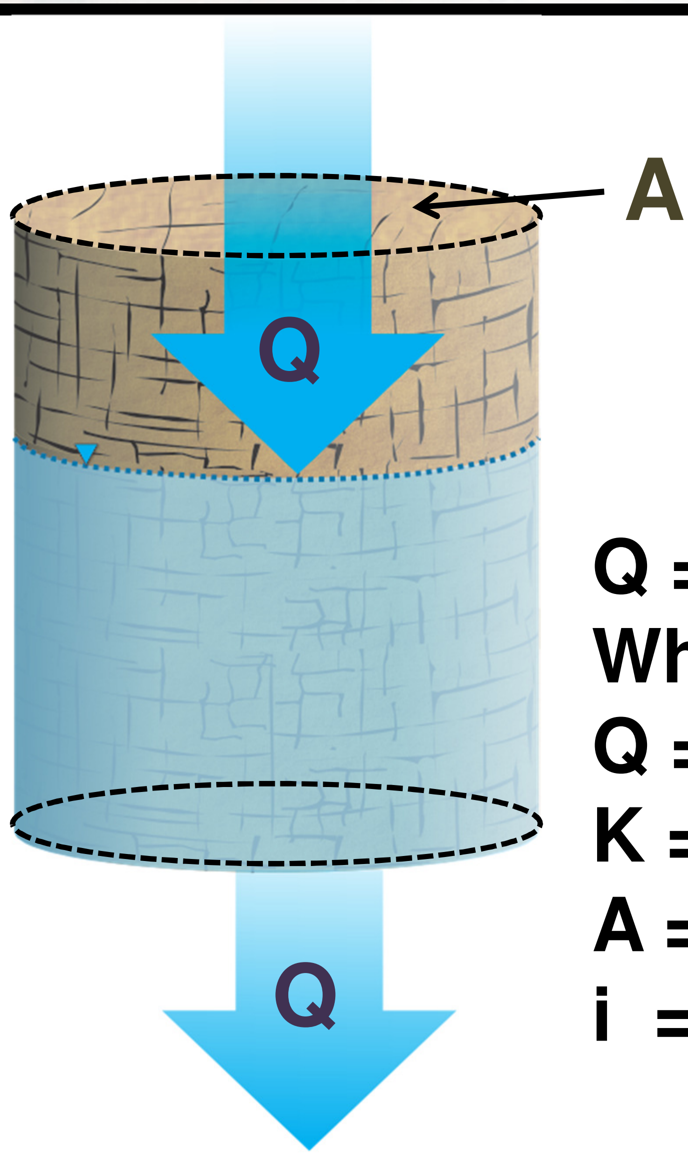


K is commonly expressed as centimeters per second (cm/s) or feet per day (ft/day)

BUT

Does not indicate groundwater velocity

Darcy's Law



Q = (K) x (A) x (i)

Where:

Q = flow rate

K = hydraulic conductivity

A = cross-sectional area

i = hydraulic gradient

Hydraulic Conductivity

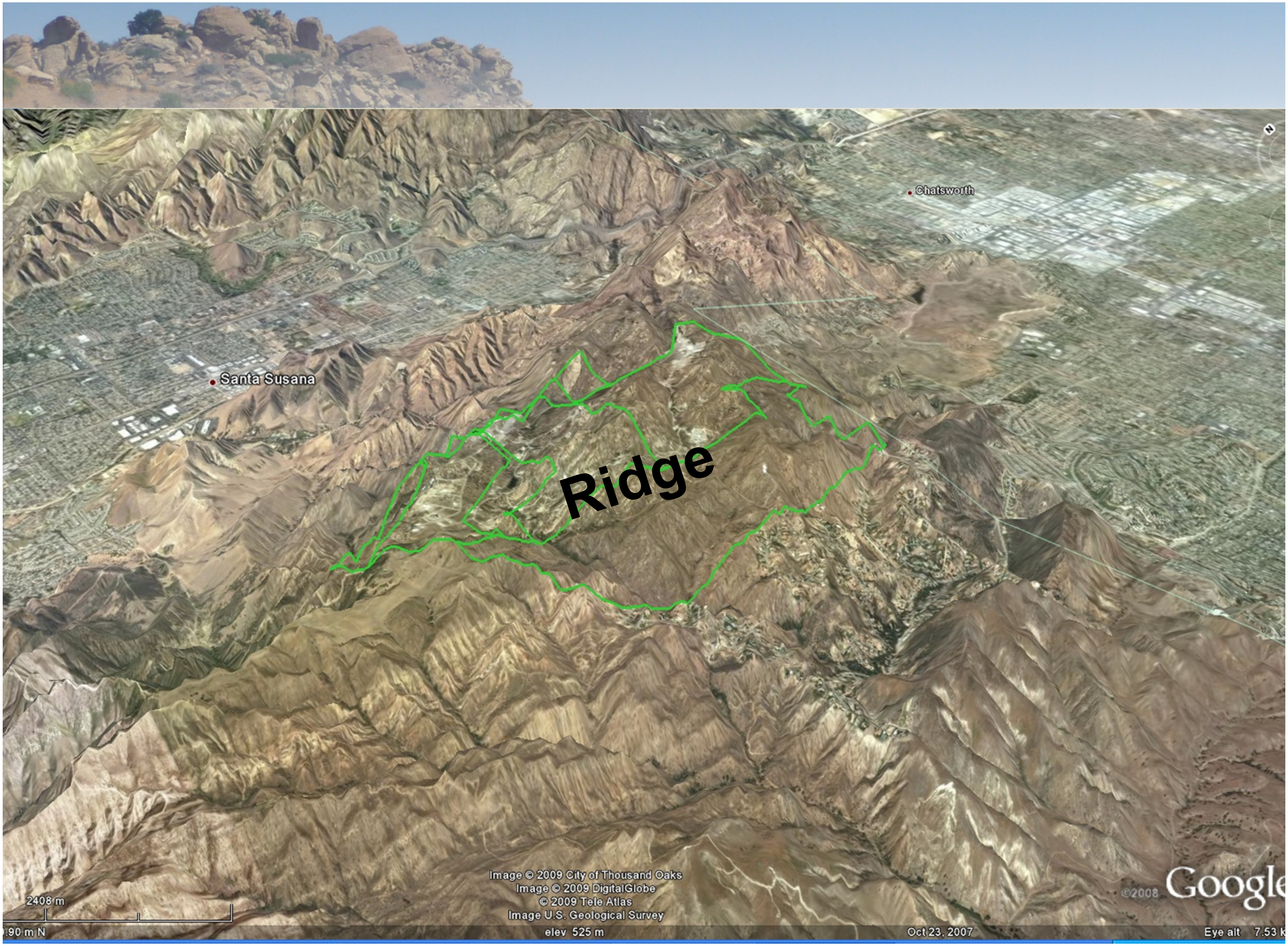
The more easily water flows, the higher the hydraulic conductivity.

K ~ 0.00000001 (10^{-8}) cm per second - Shale

K~ 0.000001 (10^{-6}) cm per second – Sandstone matrix

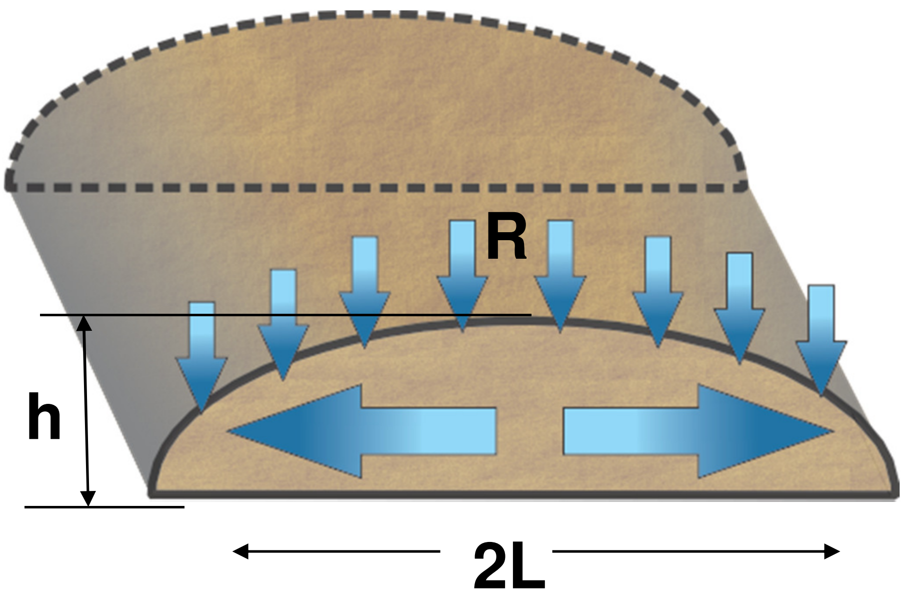
K~ 0.00001 (10^{-5}) cm per second – Fractured sandstone

K~0.01 (10^{-2}) cm per second -- Gravel



Chatsworth
Santa Susana
Ridge
Image © 2009 City of Thousand Oaks
Image © 2009 DigitalGlobe
© 2009 Tele Atlas
Image U.S. Geological Survey
2408 m
elev 525 m
Oct 23, 2007
Eye alt
©2008
Google

The Mountain Approximated as a Ridge



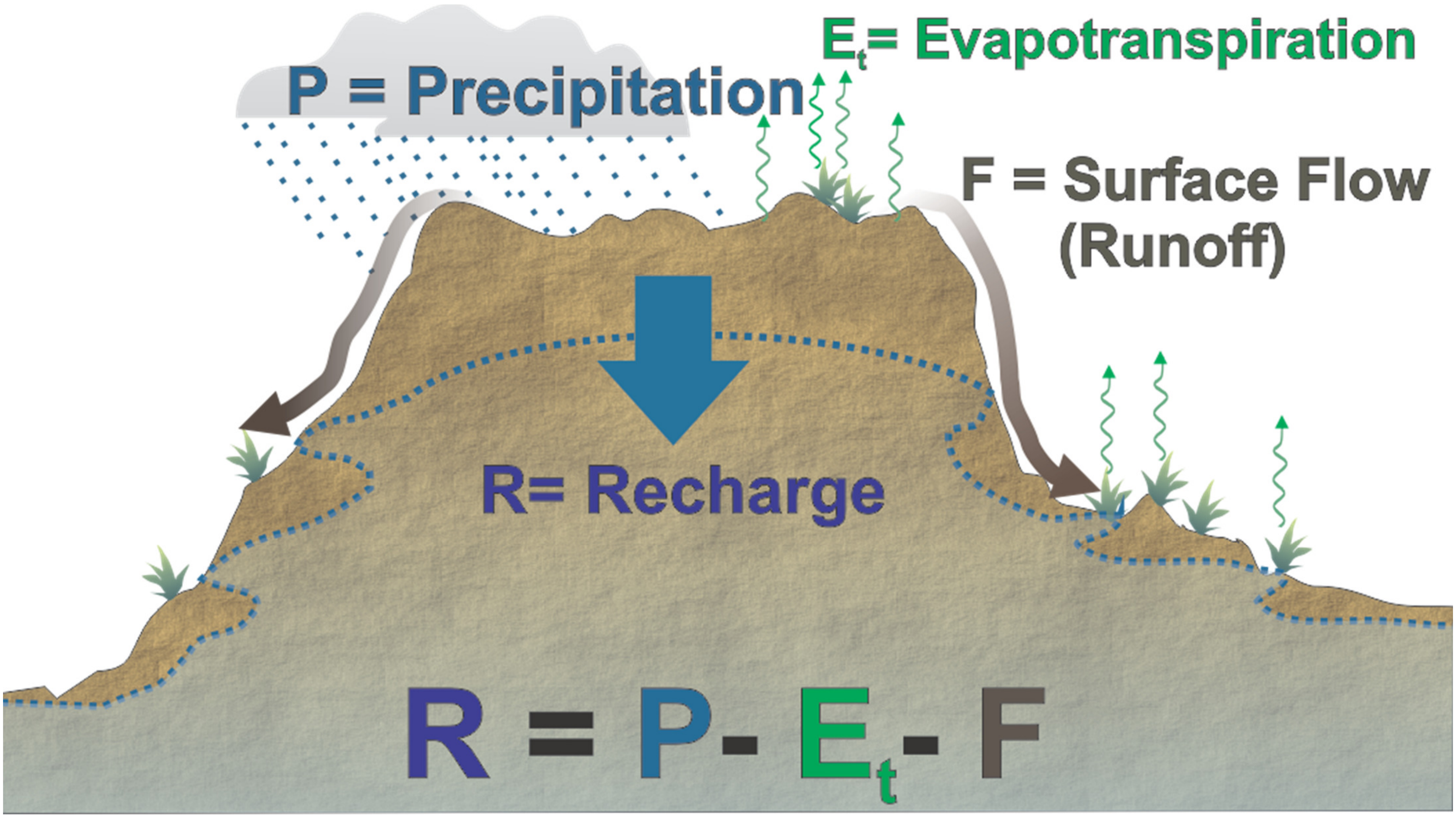
$K_b = R\,L^2 / h^2$

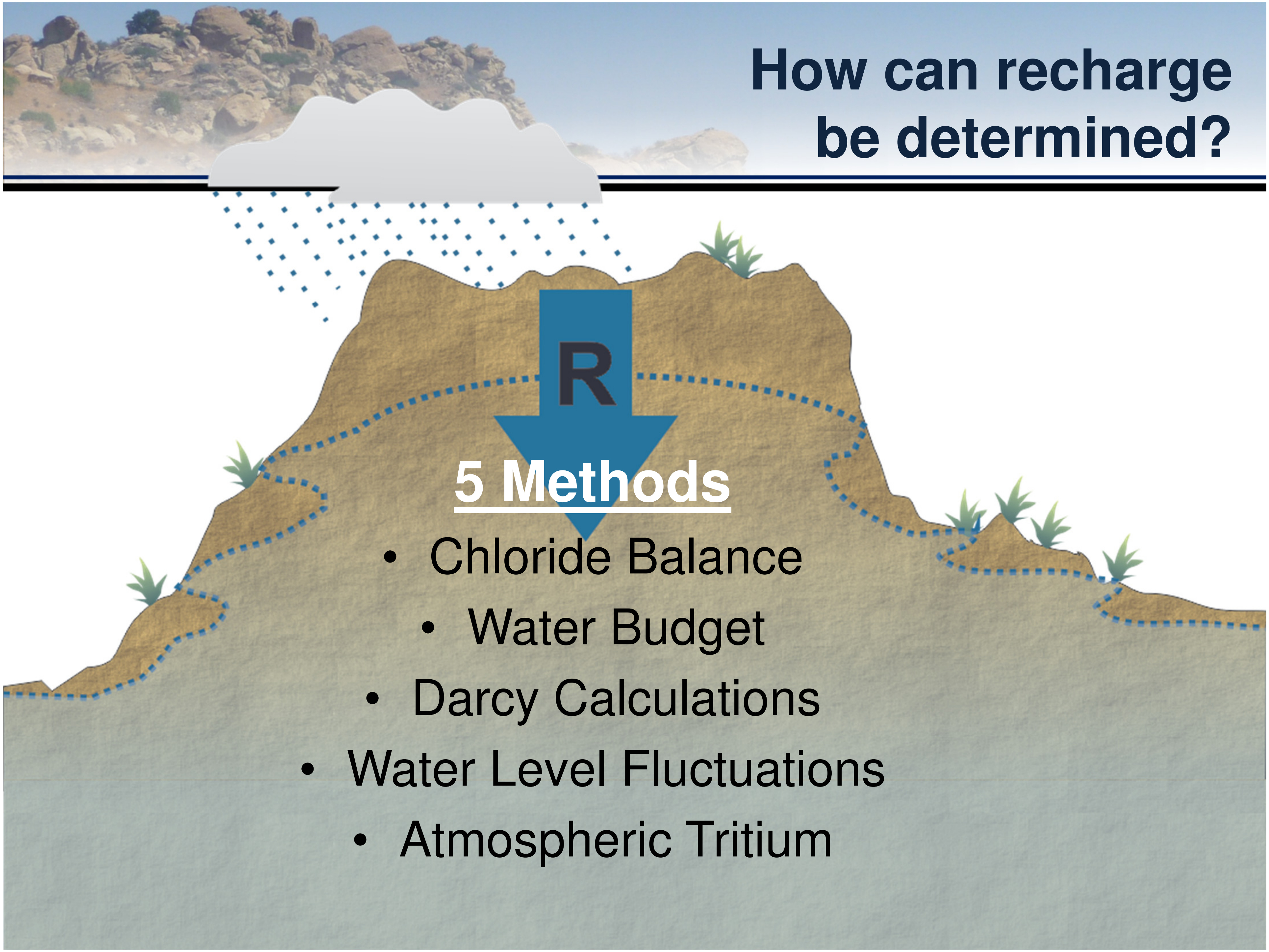
K_b = bulk hydraulic conductivity
R = recharge rate
L = width of mound
h = height of mound at center

Groundwater mound forms a long ridge of constant cross section.

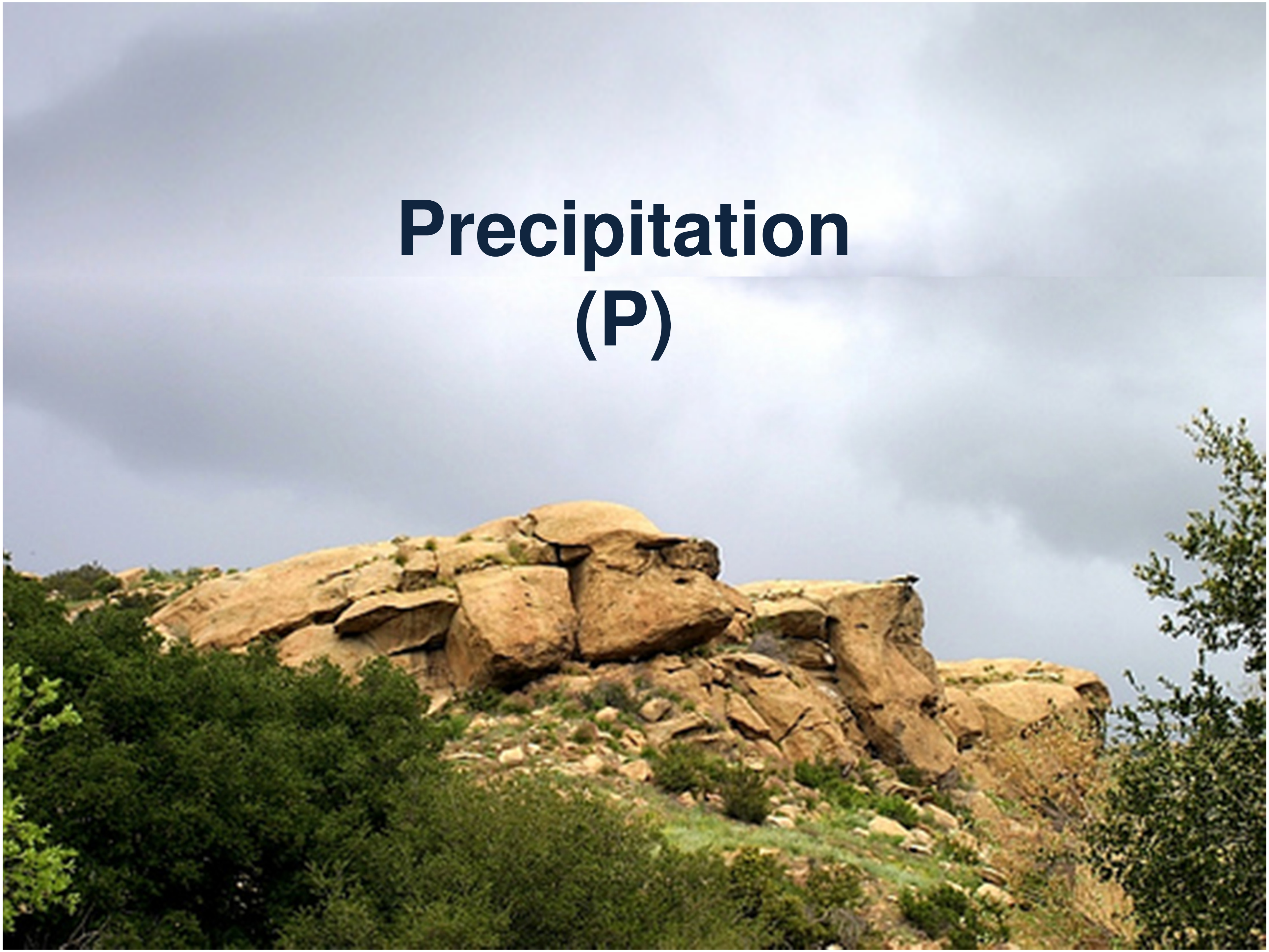
K = 0.00001 (1E-5) cm/s

Terminology

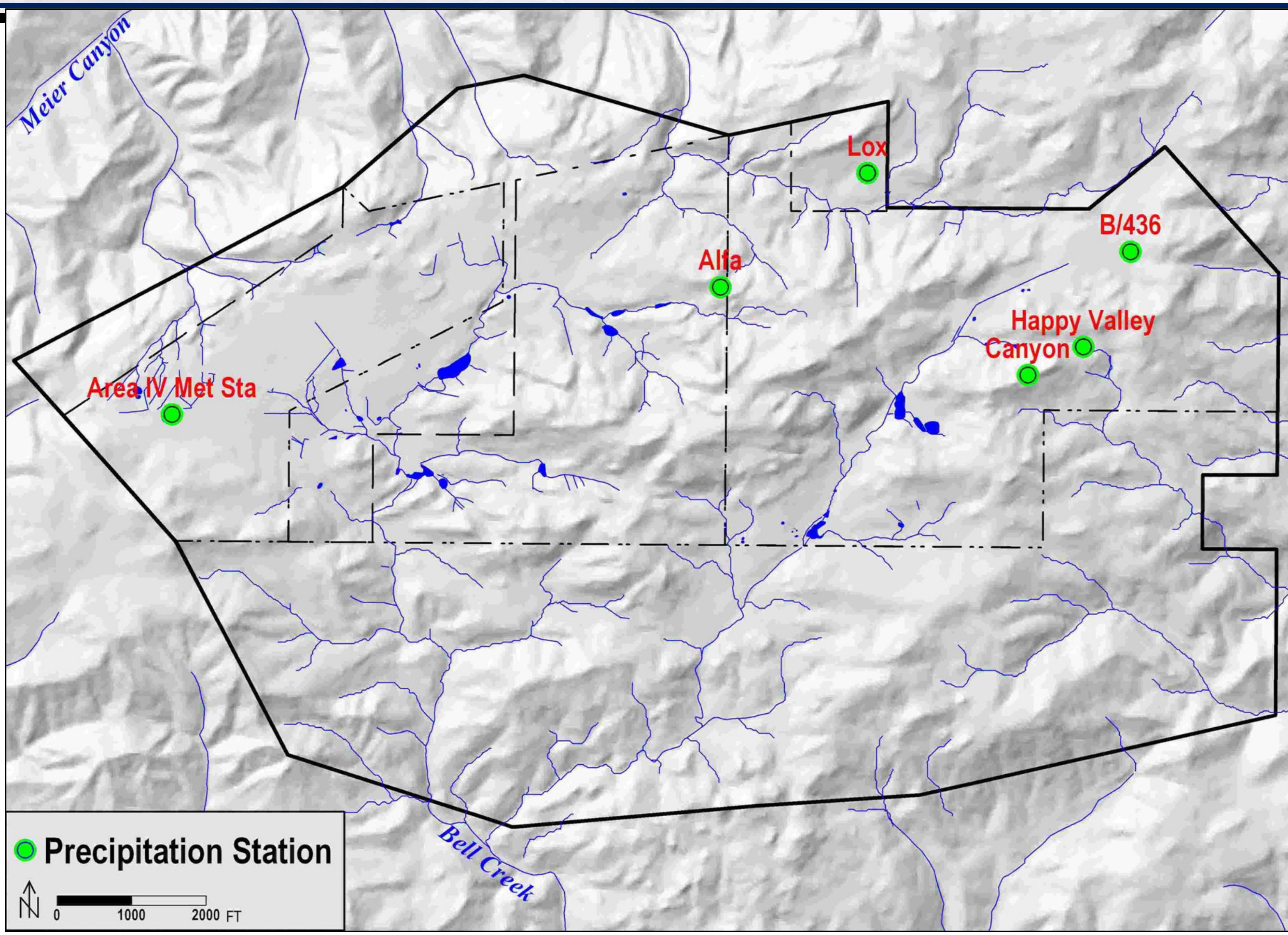



How can recharge be determined?
R
5 Methods
• Chloride Balance
• Water Budget
• Darcy Calculations
• Water Level Fluctuations
• Atmospheric Tritium

Precipitation
(P)

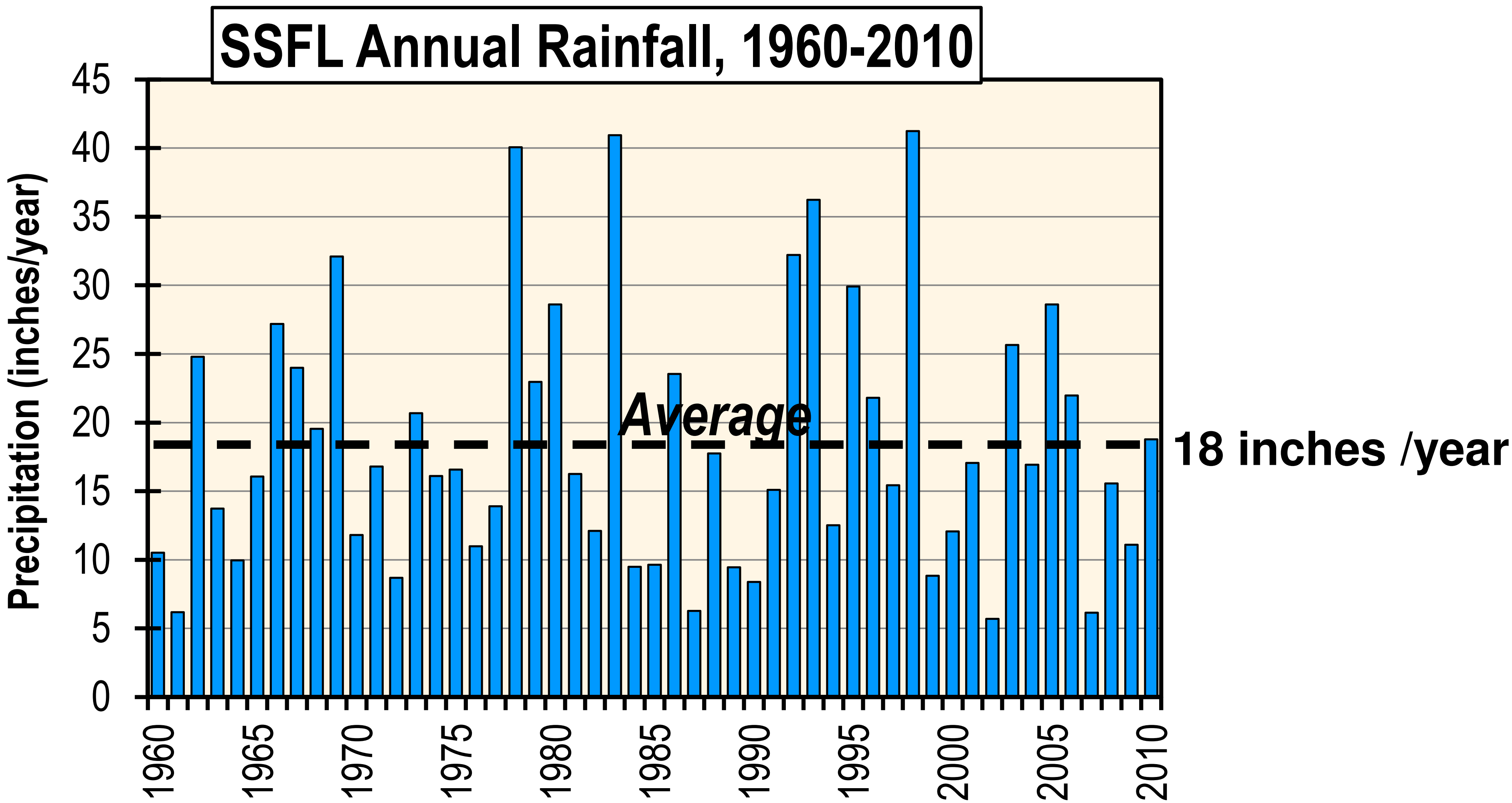


Five Precipitation Stations

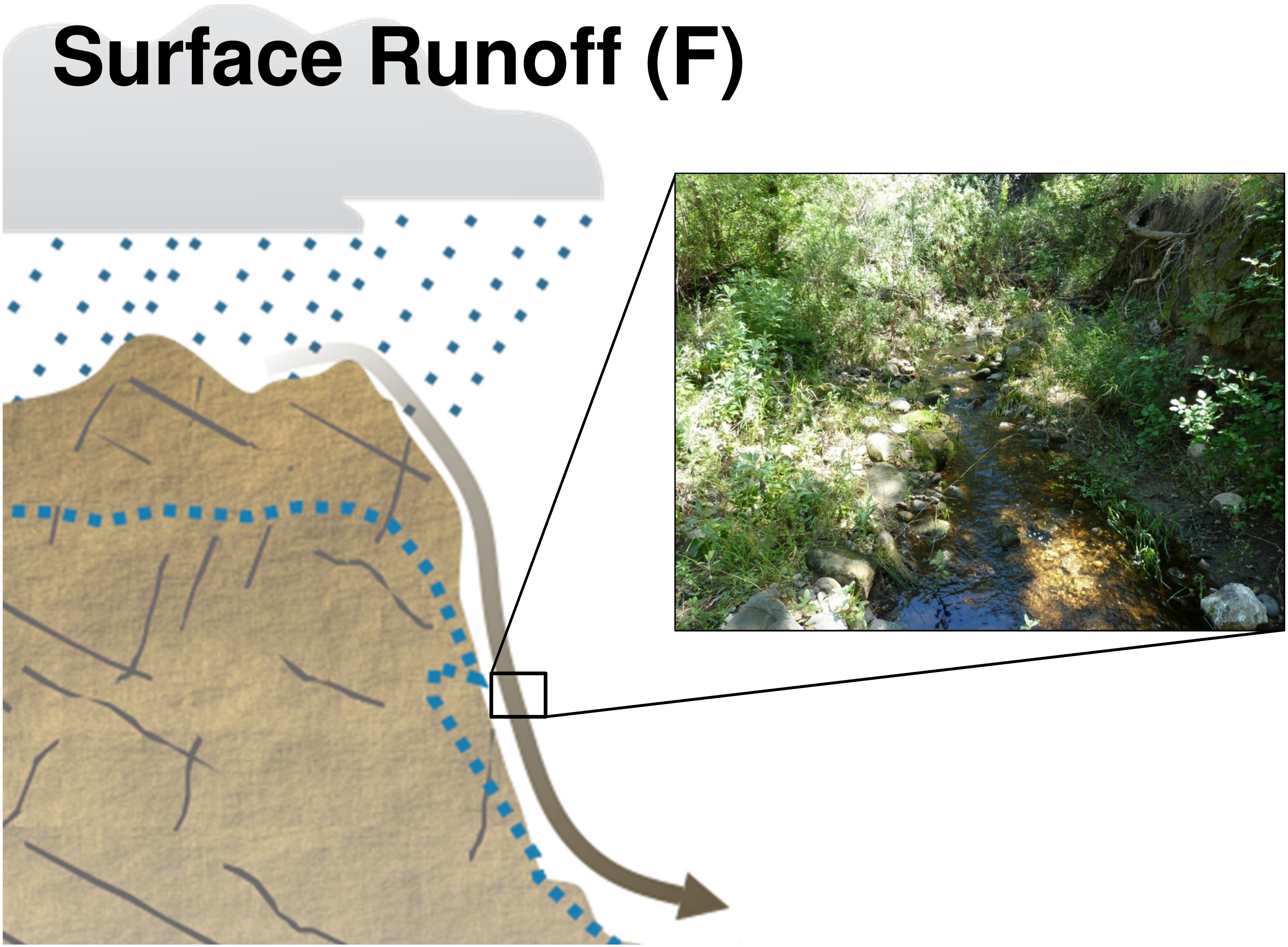


Meteorological Station

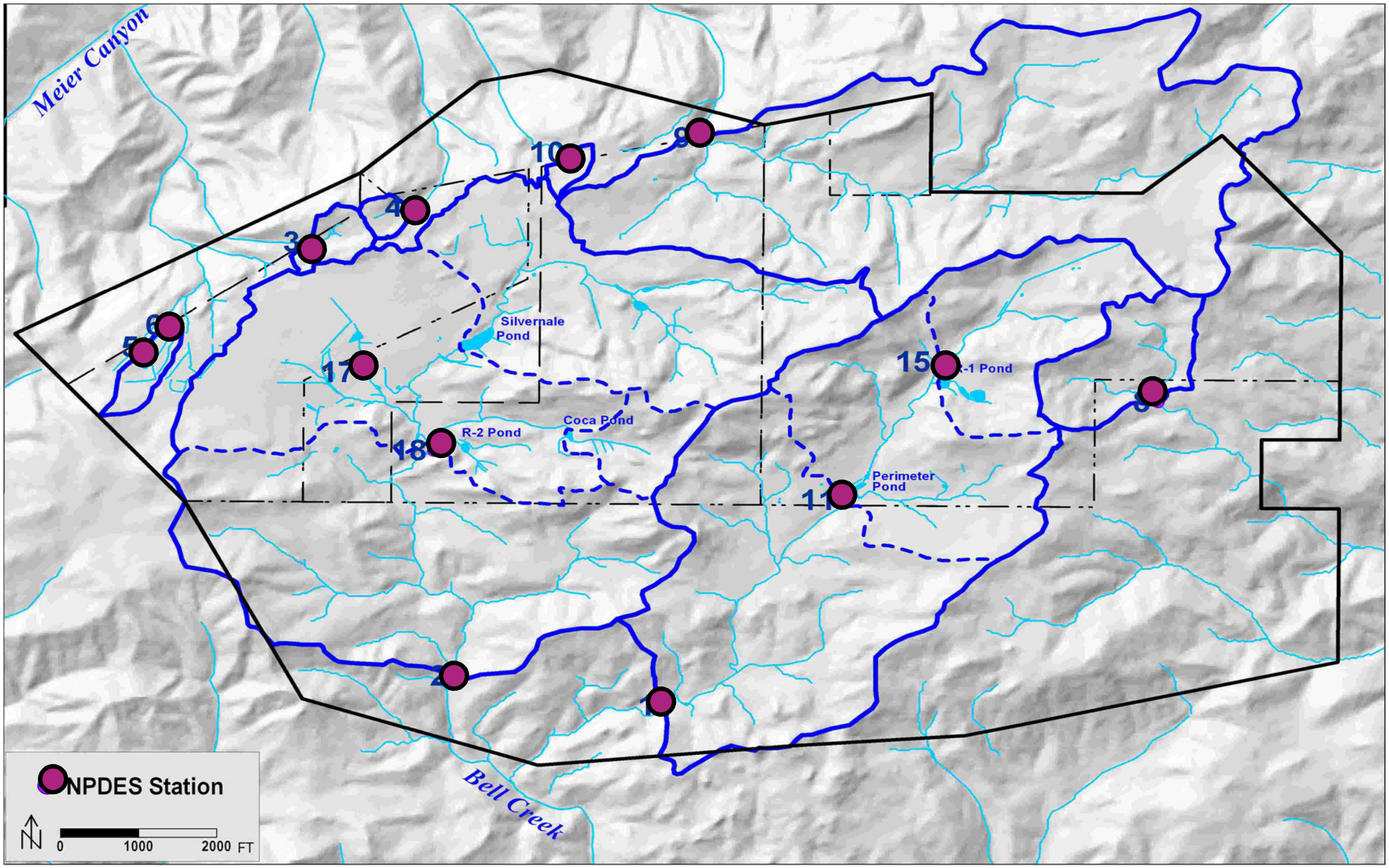
Precipitation



Surface Runoff (F)



Runoff Stations



Flume & measuring devices at outfall 8 on east side of site

Surface Runoff

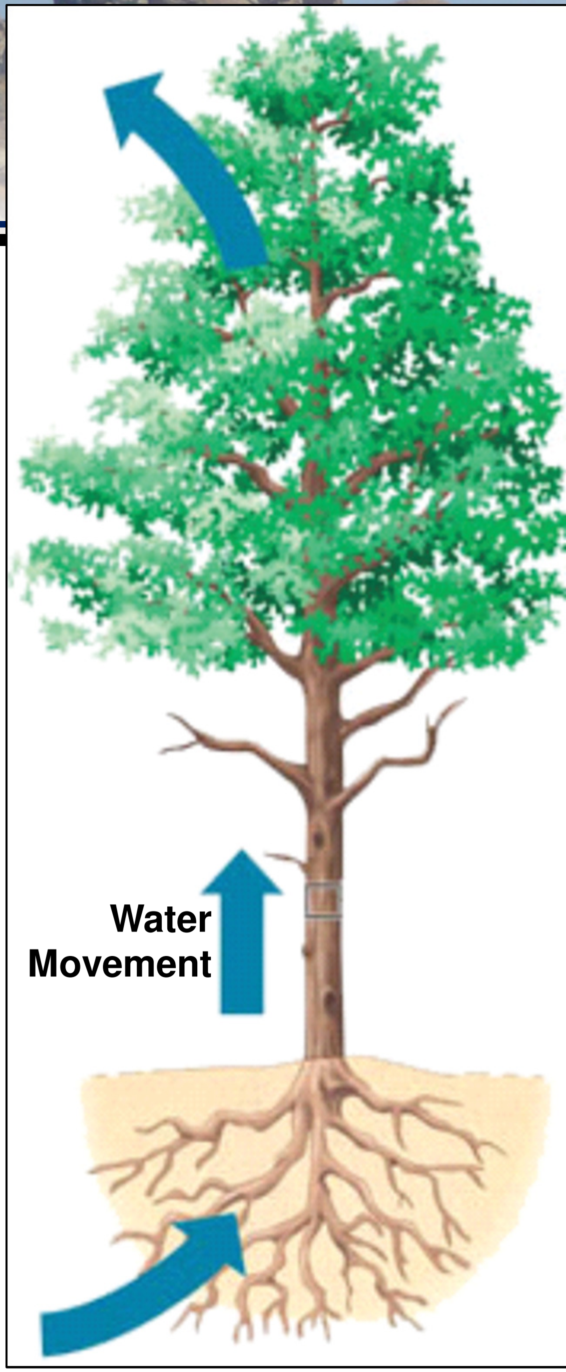
Assign: $F = 0$

Therefore: $R = 18 - E_t$

When F is assigned 0, recharge is overestimated, but within the error of two big numbers

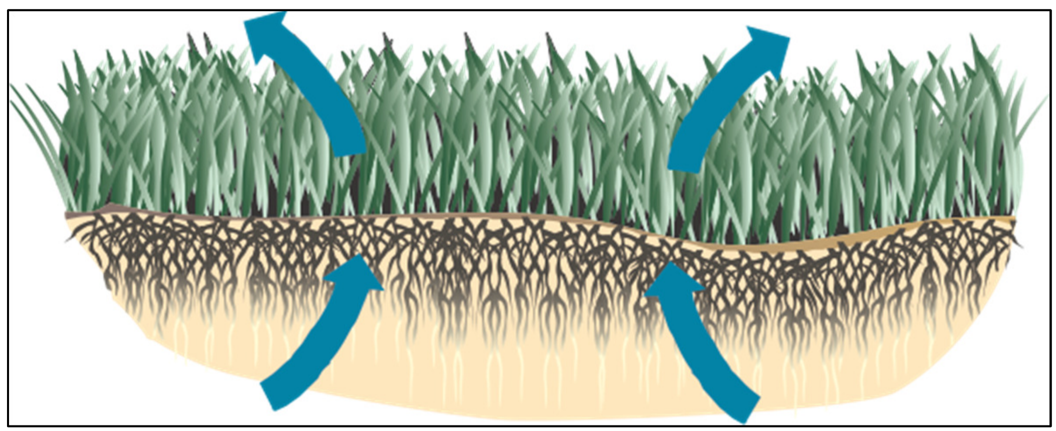

Transpiration

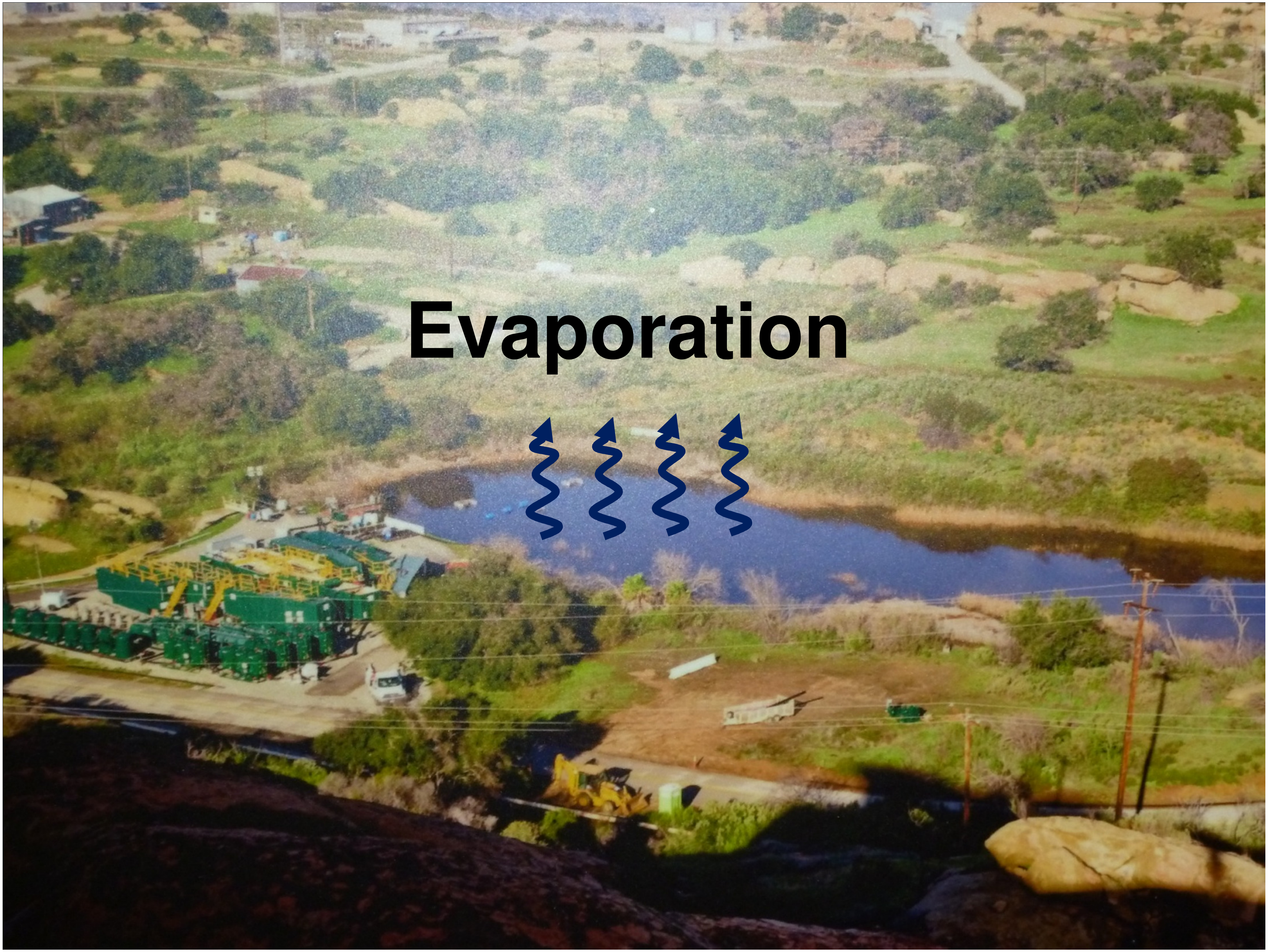
Transpiration



Transpiration:

The loss of water vapour from parts of plants (similar to sweating), especially in leaves but also in stems, flowers and roots

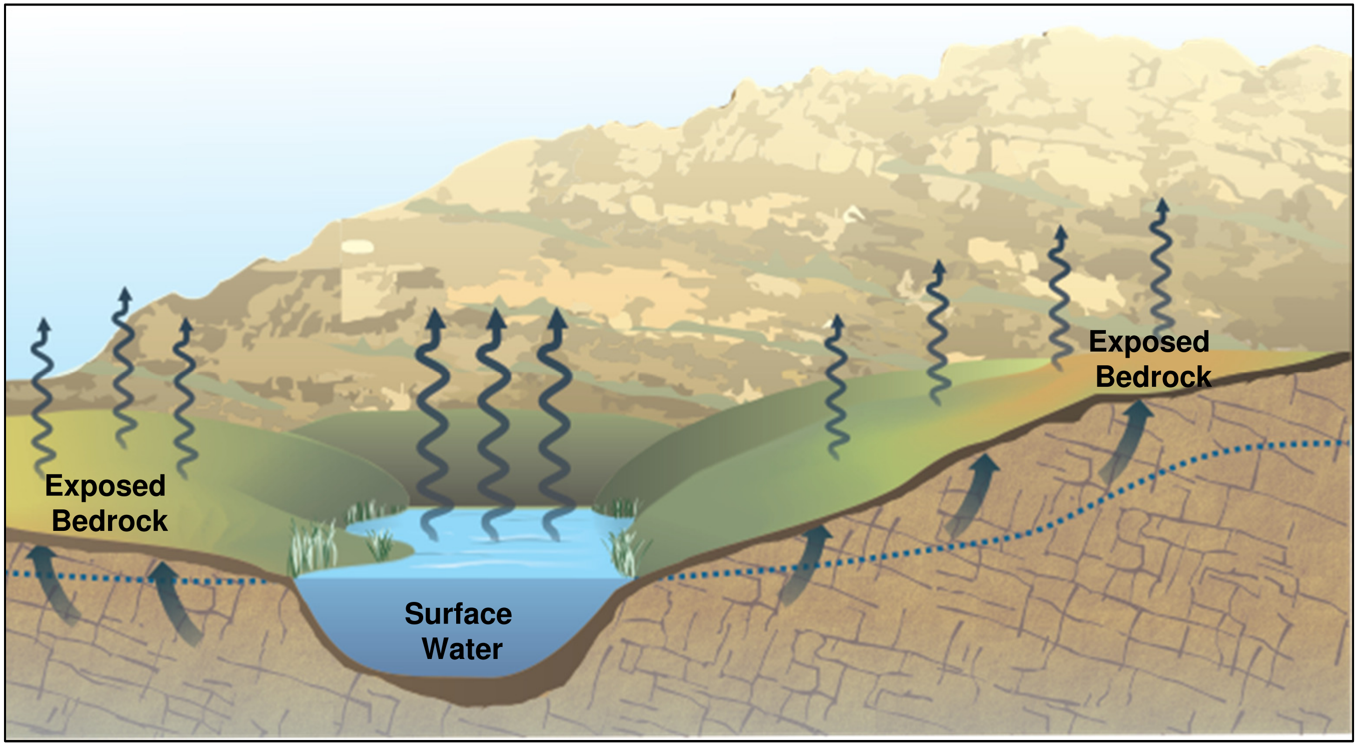



Evaporation

Evaporation (E)

Evaporation:

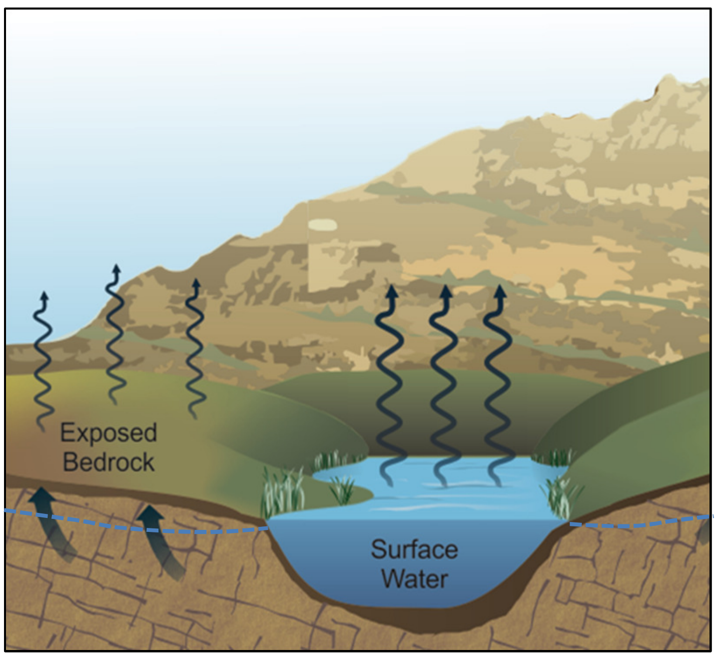
The loss of water vapour from
the ground surface and surface water bodies



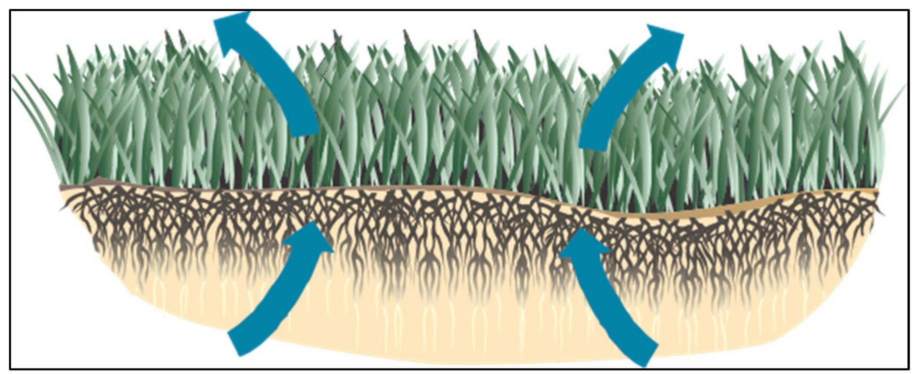
Evapotranspiration (E_t)

Evapotranspiration:

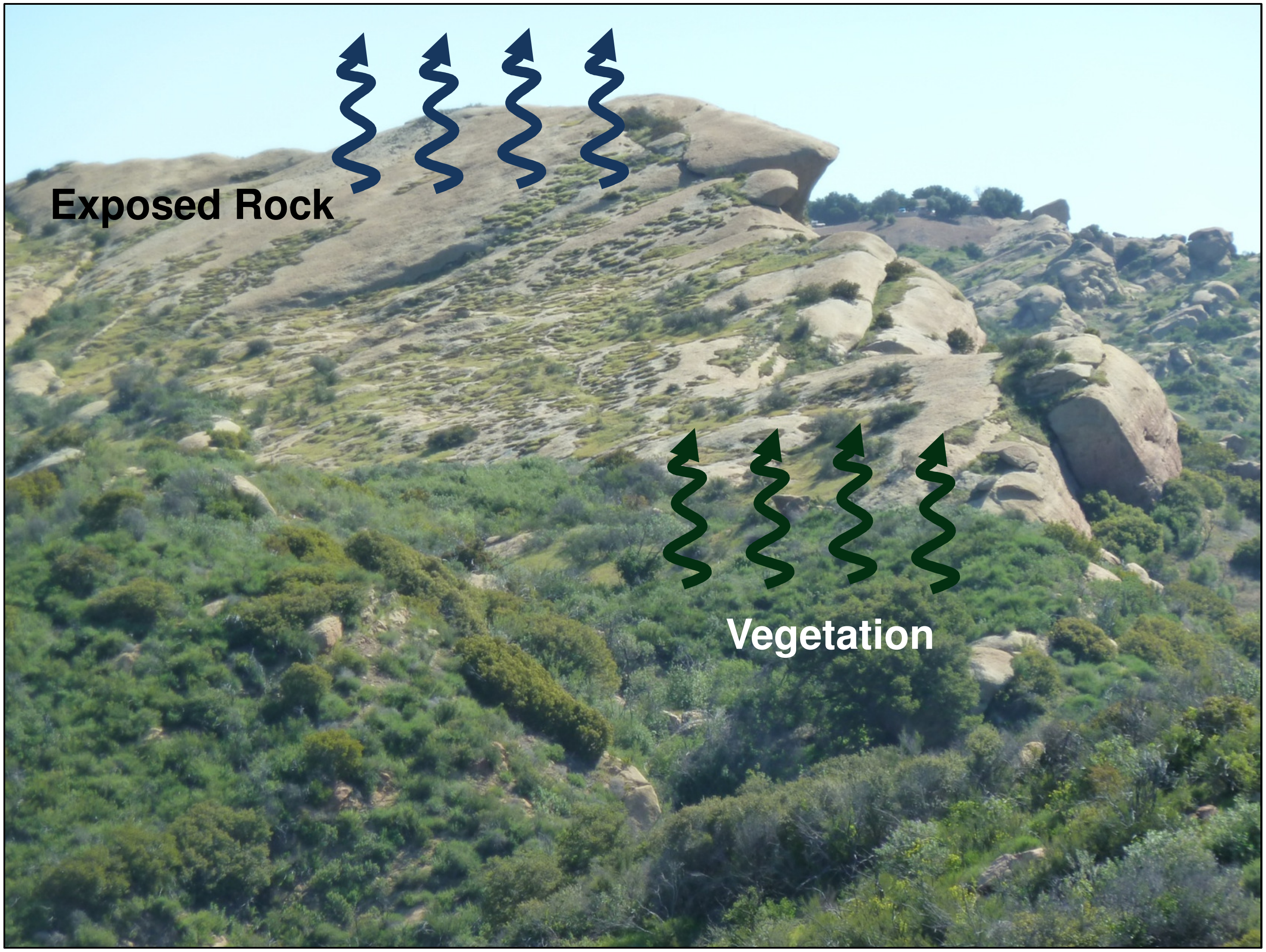
the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere



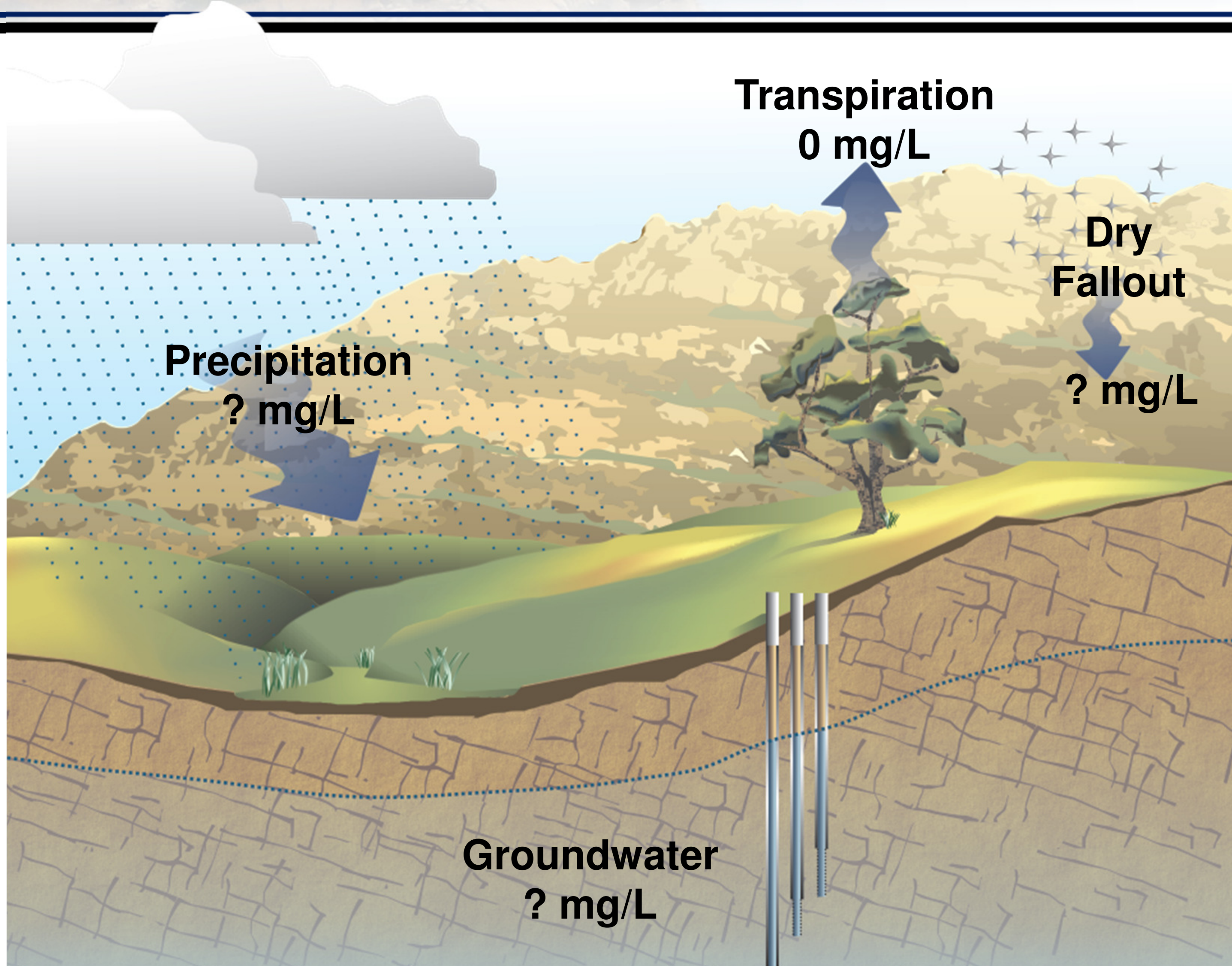
+



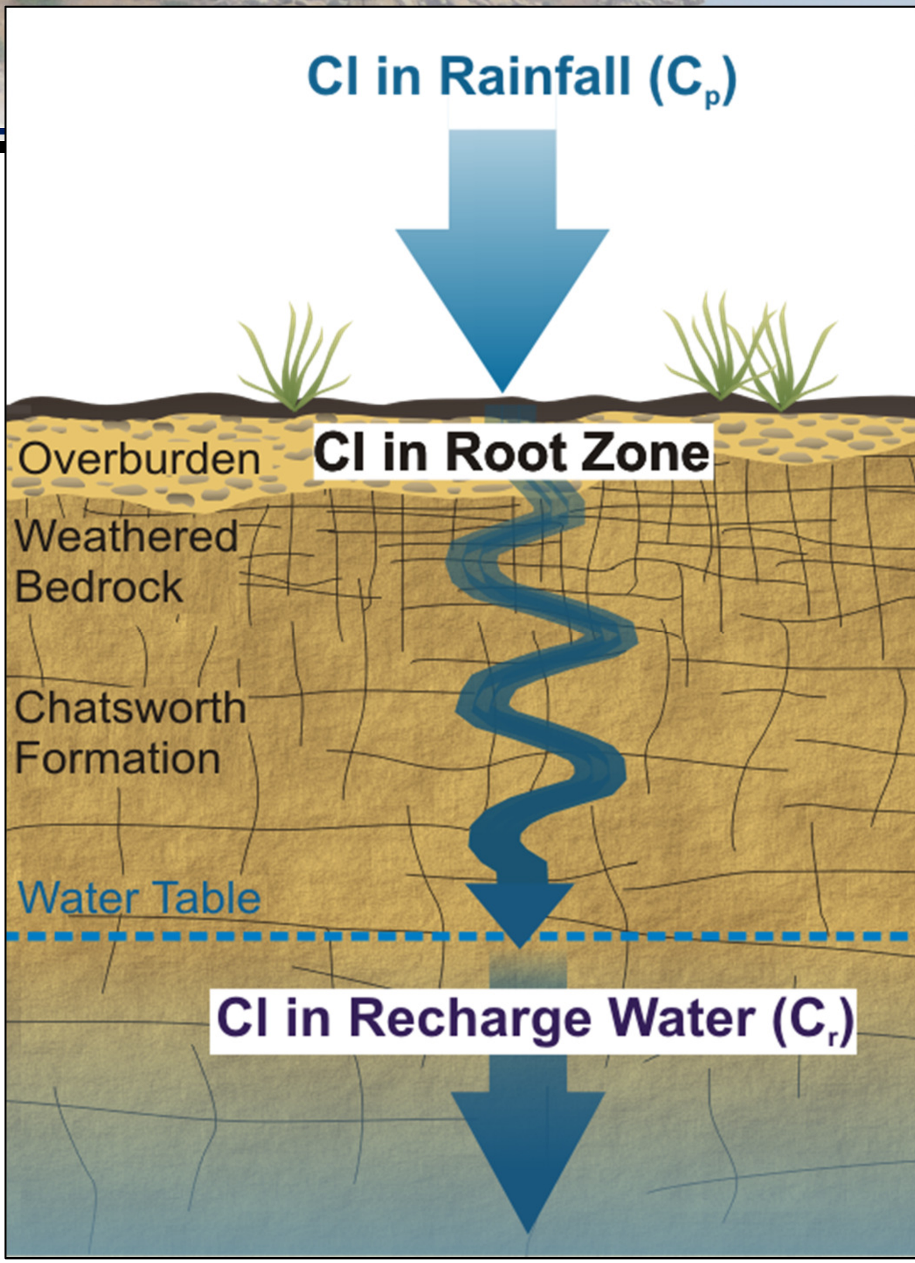
Evapotranspiration



Chloride Balance



Chloride Balance



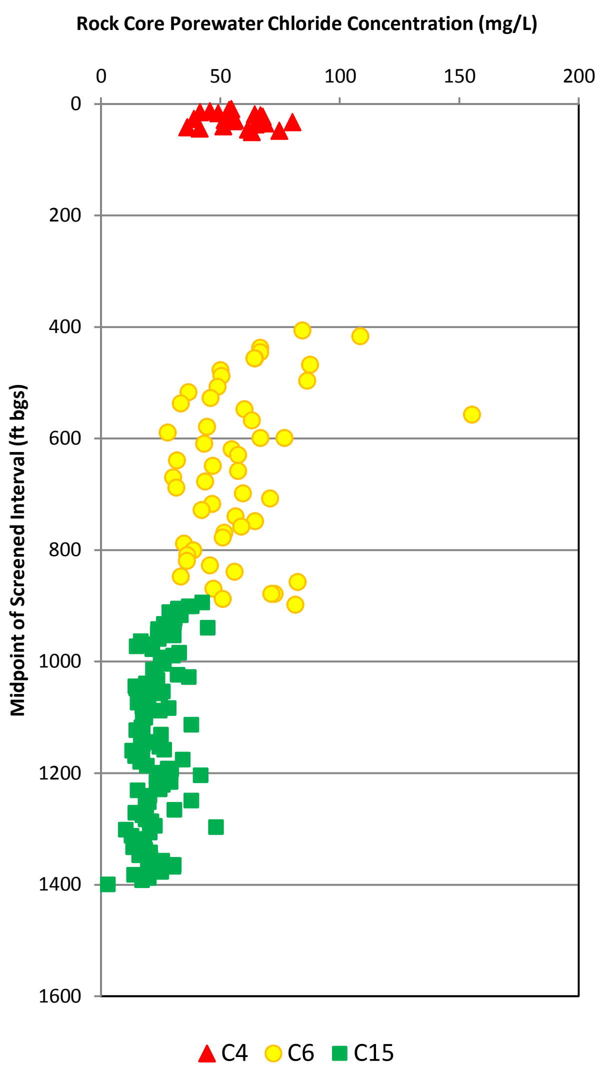
Chloride is added to the root zone from rainfall.

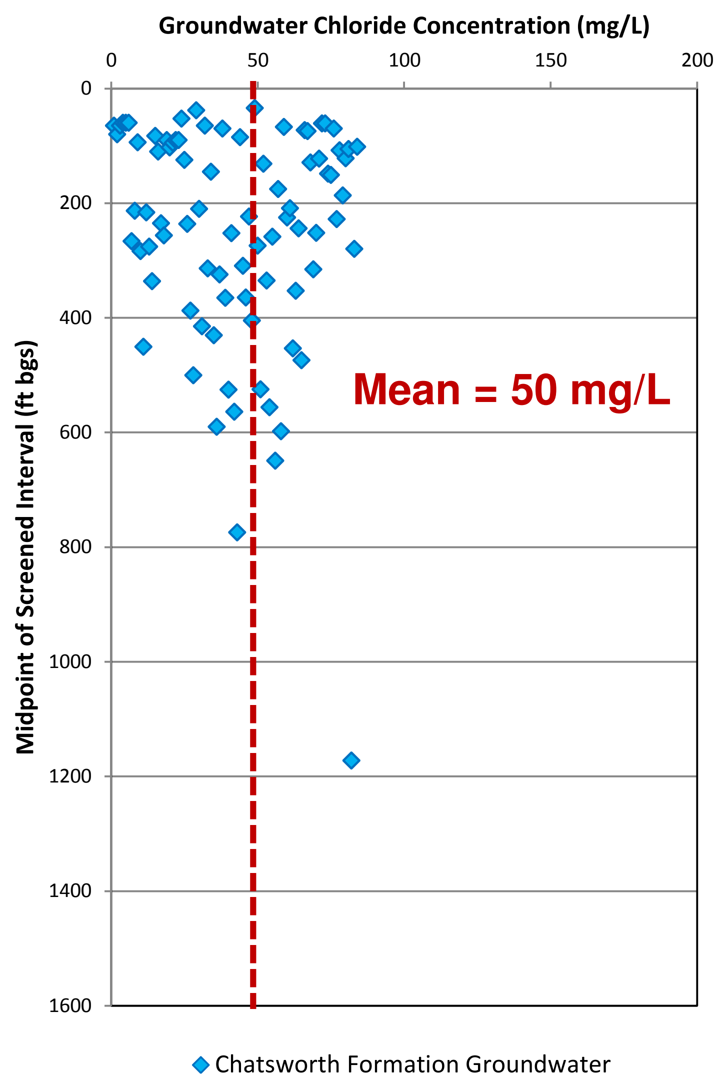
Chloride is leached downward from the root zone by recharge water.

Long term chloride inputs must equal long term removal.

$$R = \{C_p / C_r\} P$$

Changes in Chloride with depth

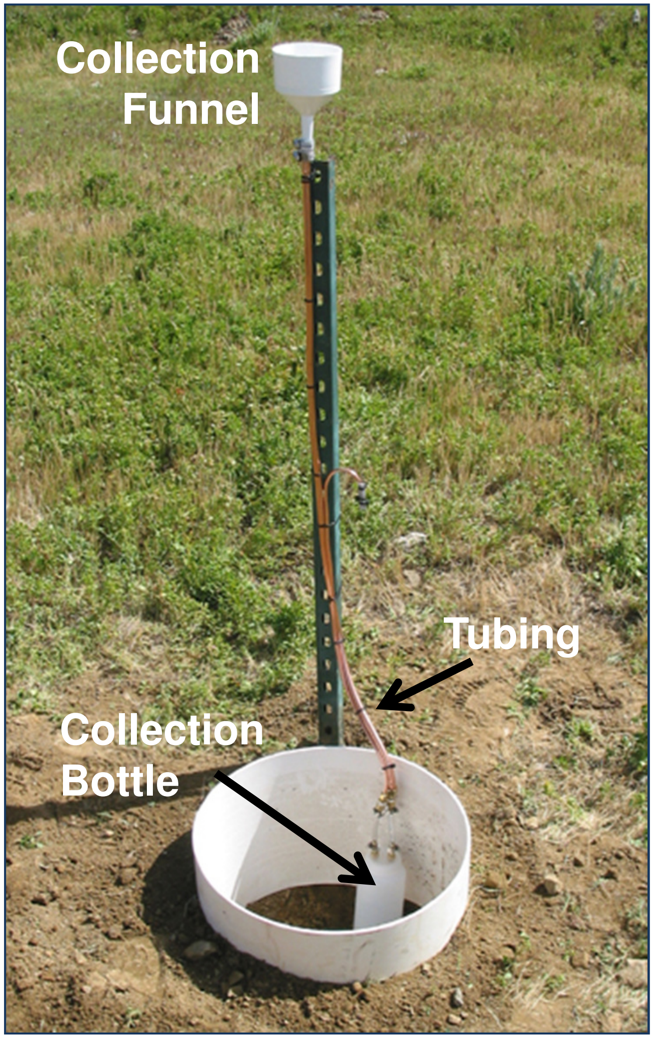




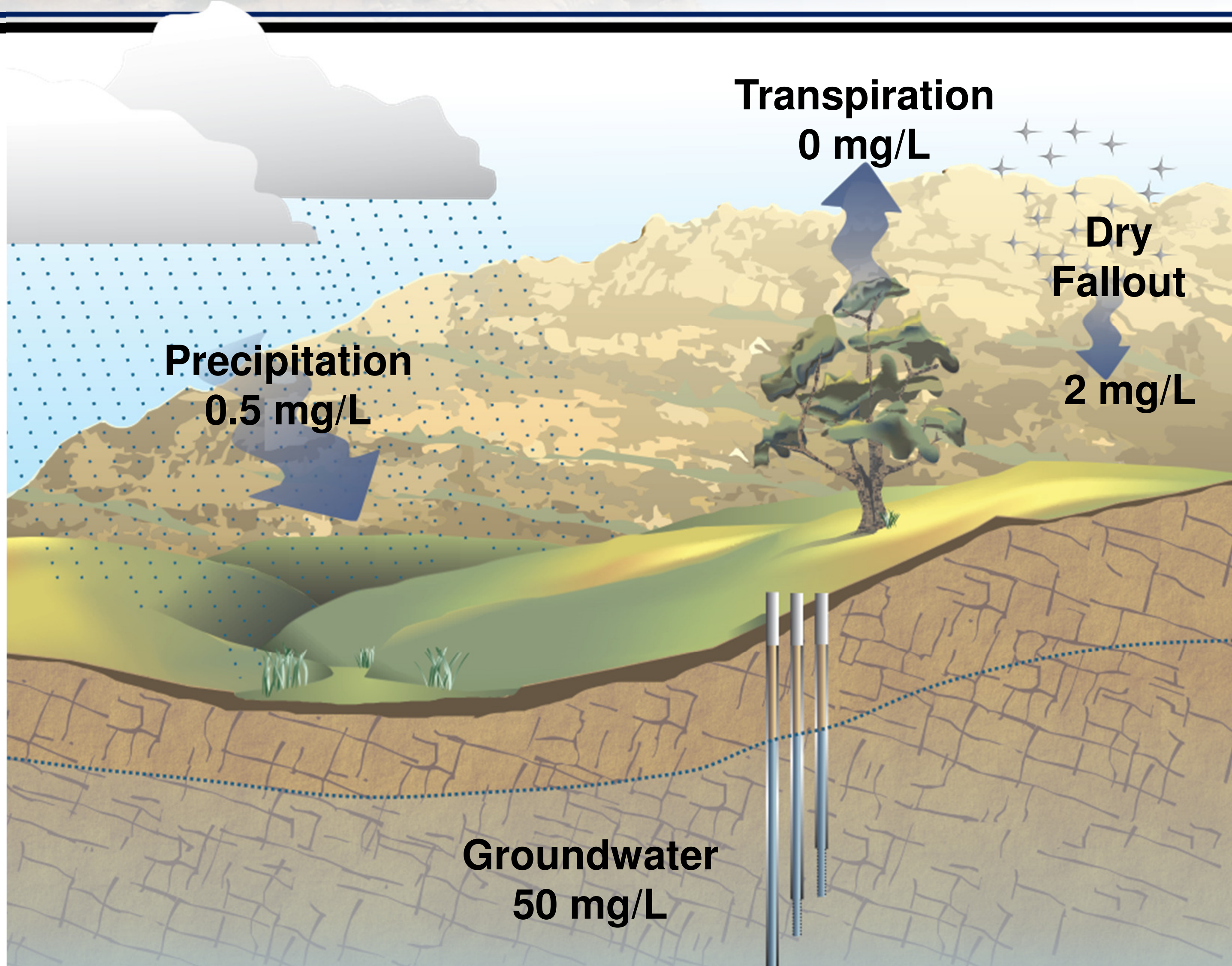
Bulk Deposition Collector

Collects both chloride in dry fall and rainfall.

Dry fall deposited in the collection funnel is periodically flushed down into the storage bottle by rainfall.



Chloride Balance



HOW MUCH RECHARGE?

Chloride Mass Balance

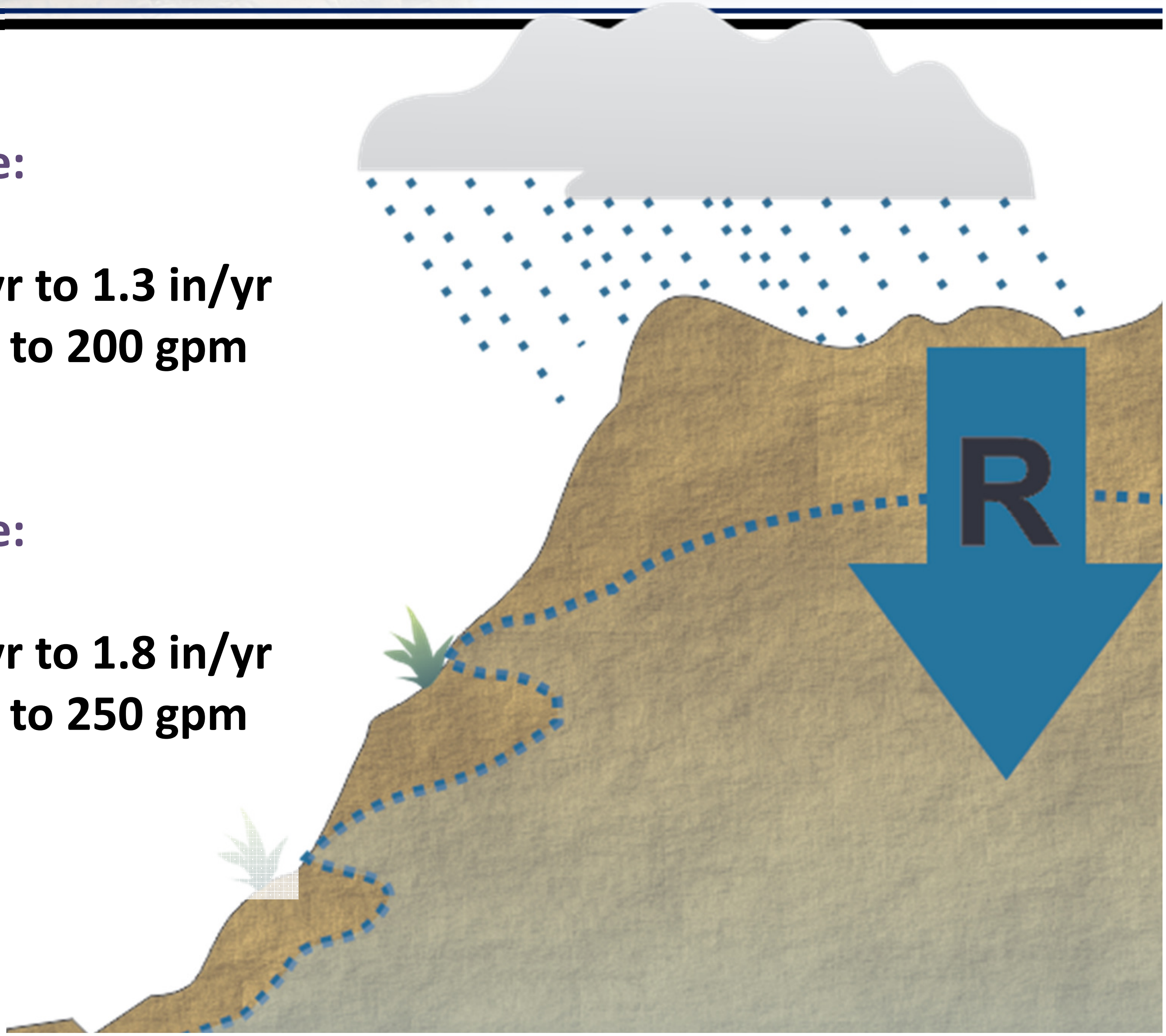
Recharge Range:

0.4 in/yr to 1.3 in/yr
60 gpm to 200 gpm

Other Methods

Recharge Range:

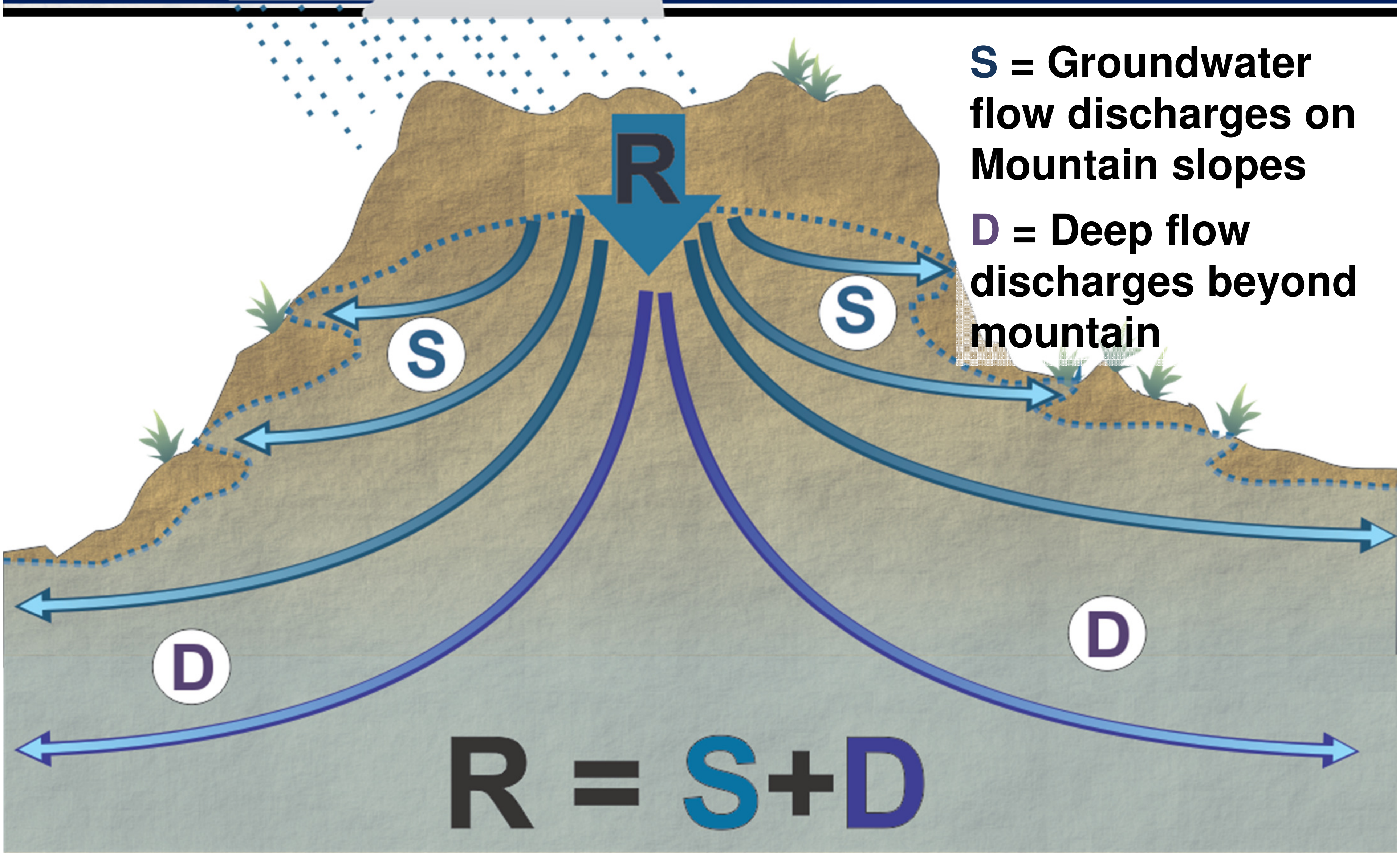
0.4 in/yr to 1.8 in/yr
60 gpm to 250 gpm



Gallons per Minute (gpm)

Garden Hose discharging at 5 gpm

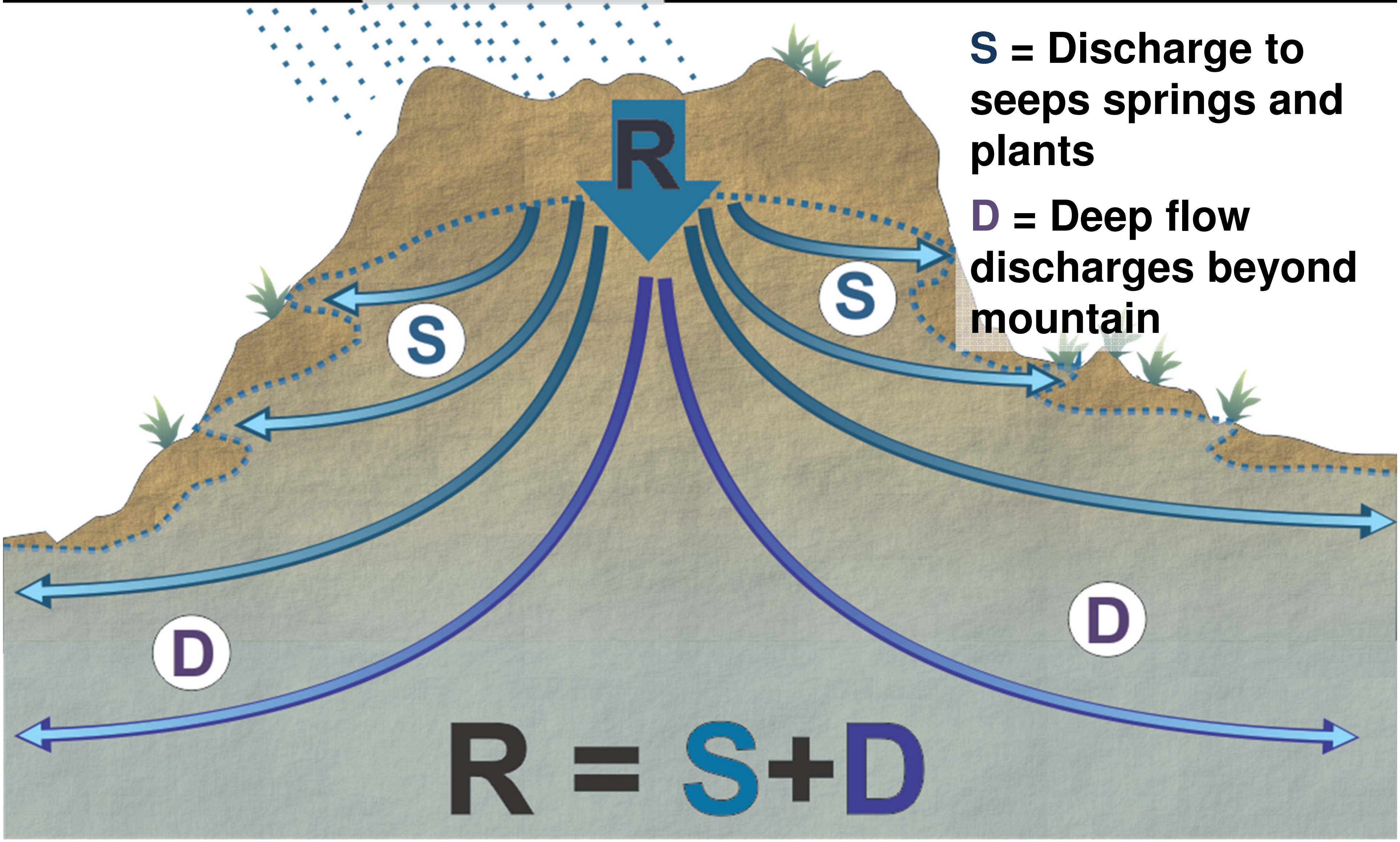
Where does the recharge water go?



S = Groundwater flow discharges on Mountain slopes

D = Deep flow discharges beyond mountain

Where does the recharge water go?

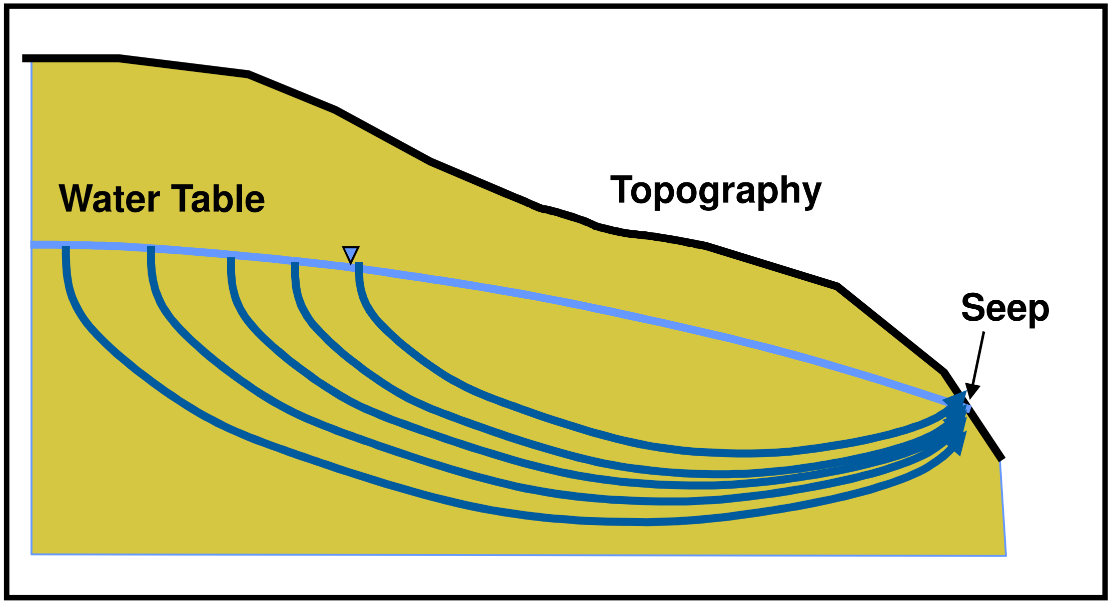


S = Discharge to seeps springs and plants

D = Deep flow discharges beyond mountain

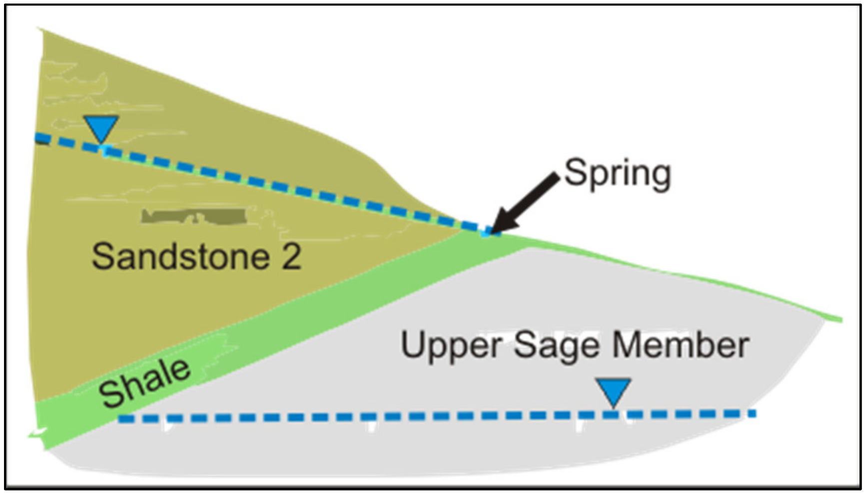

Seeps

Causes of Seeps: Topography

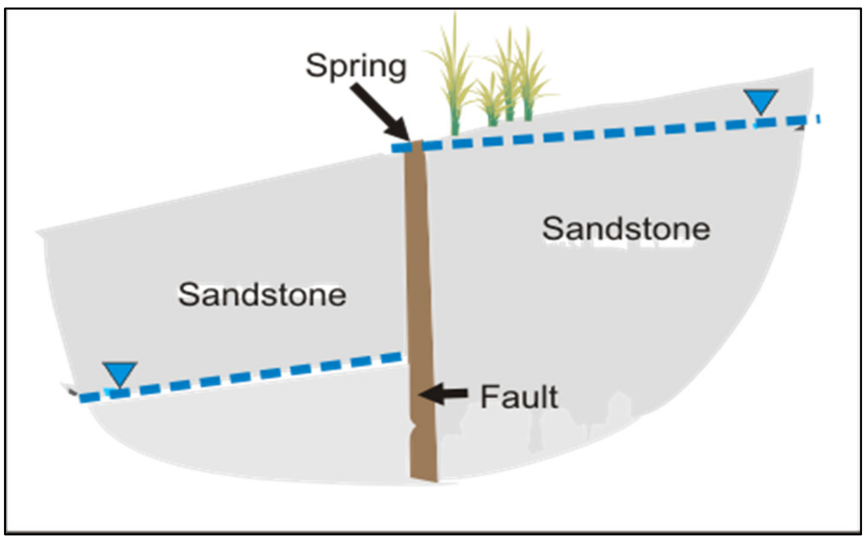


Seep occurs where water table intersects mountain slope

Causes of Seeps: Geology



Seep occurs where shale directs groundwater to surface

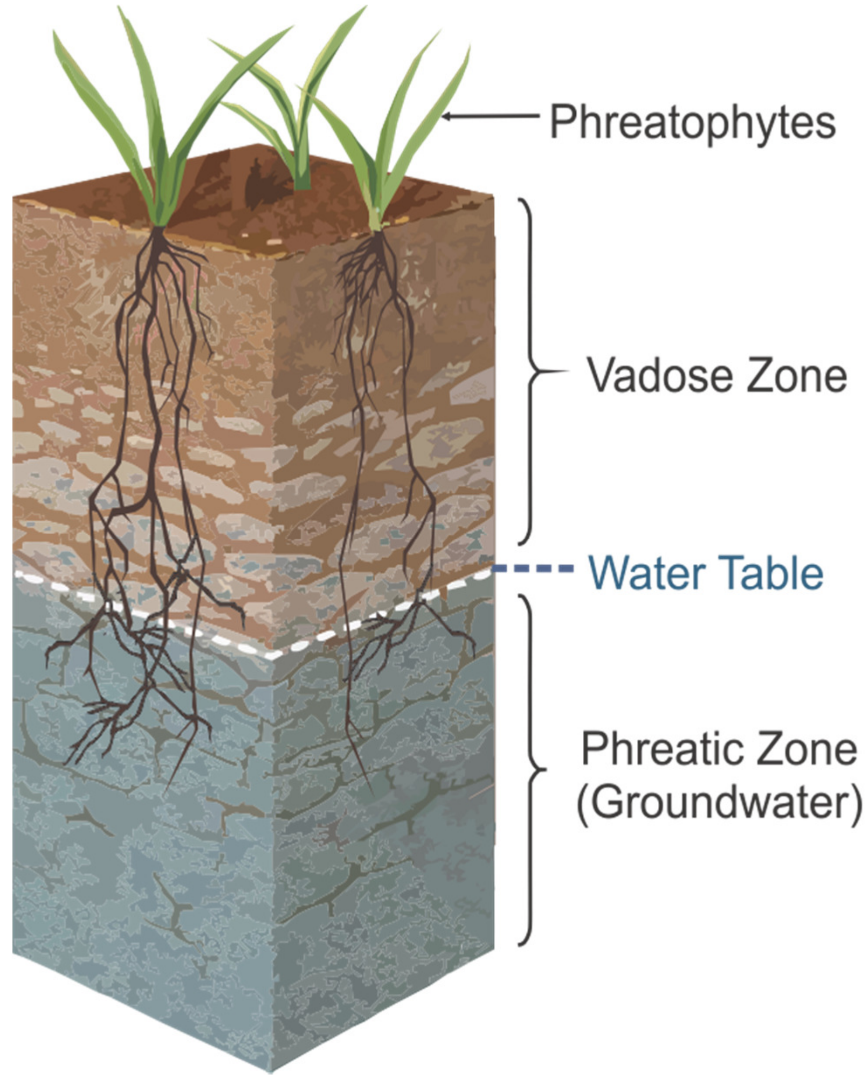


Seep occurs where fault directs groundwater to surface

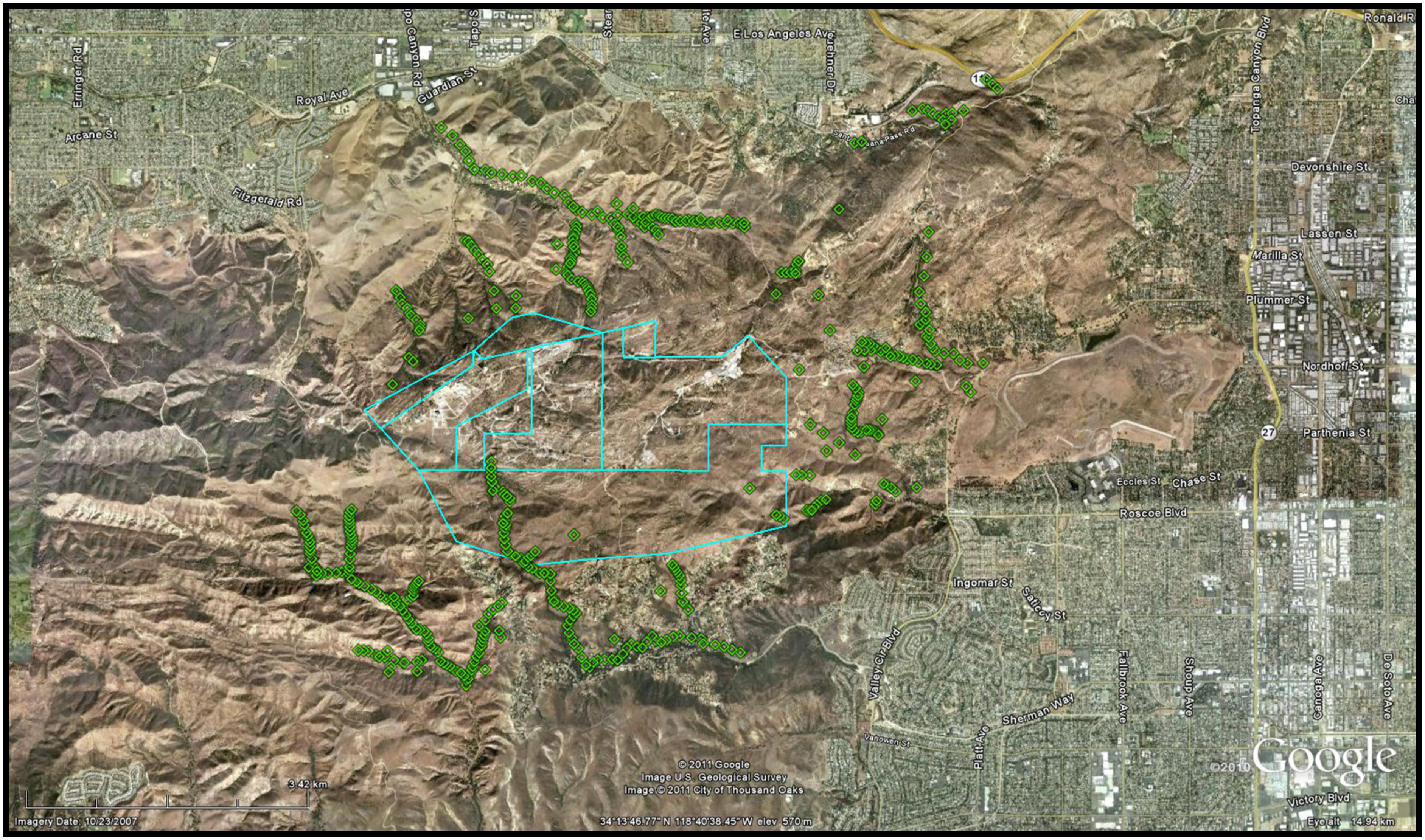
Transpiration

Phreatophytes

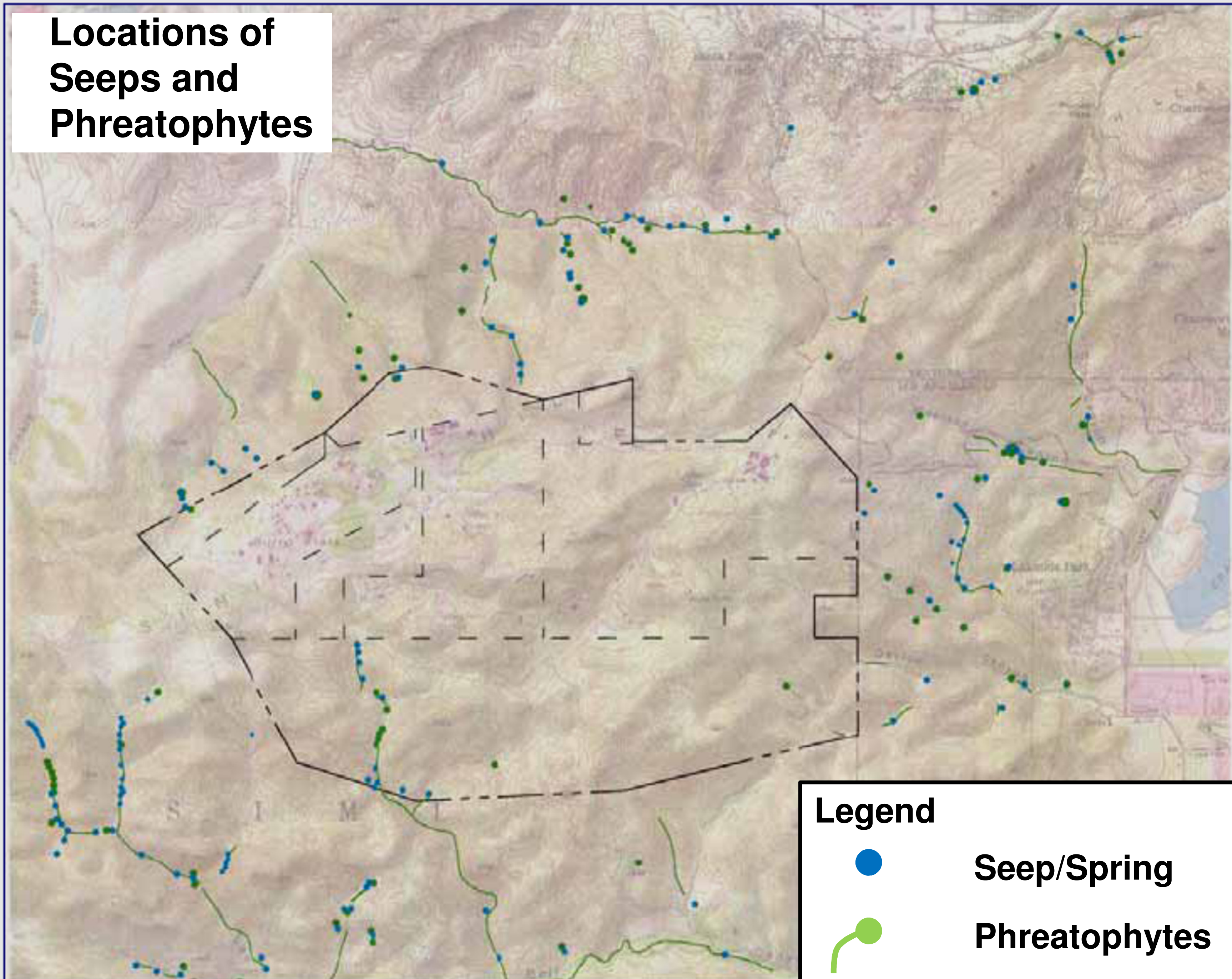
Deep-rooted plant that obtains much of its water from the phreatic zone (groundwater)



Location of Phreatophytes



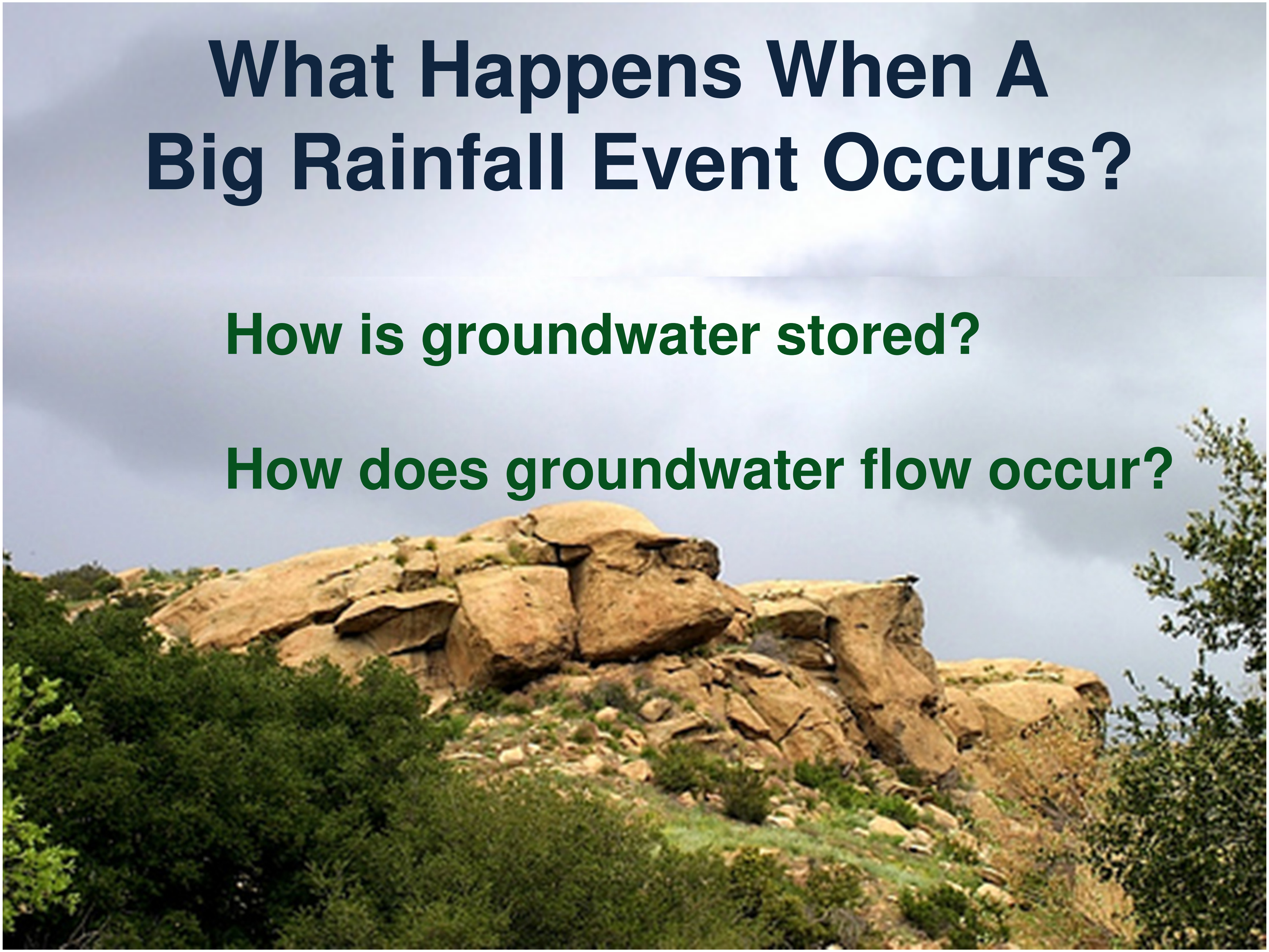
Locations of Seeps and Phreatophytes



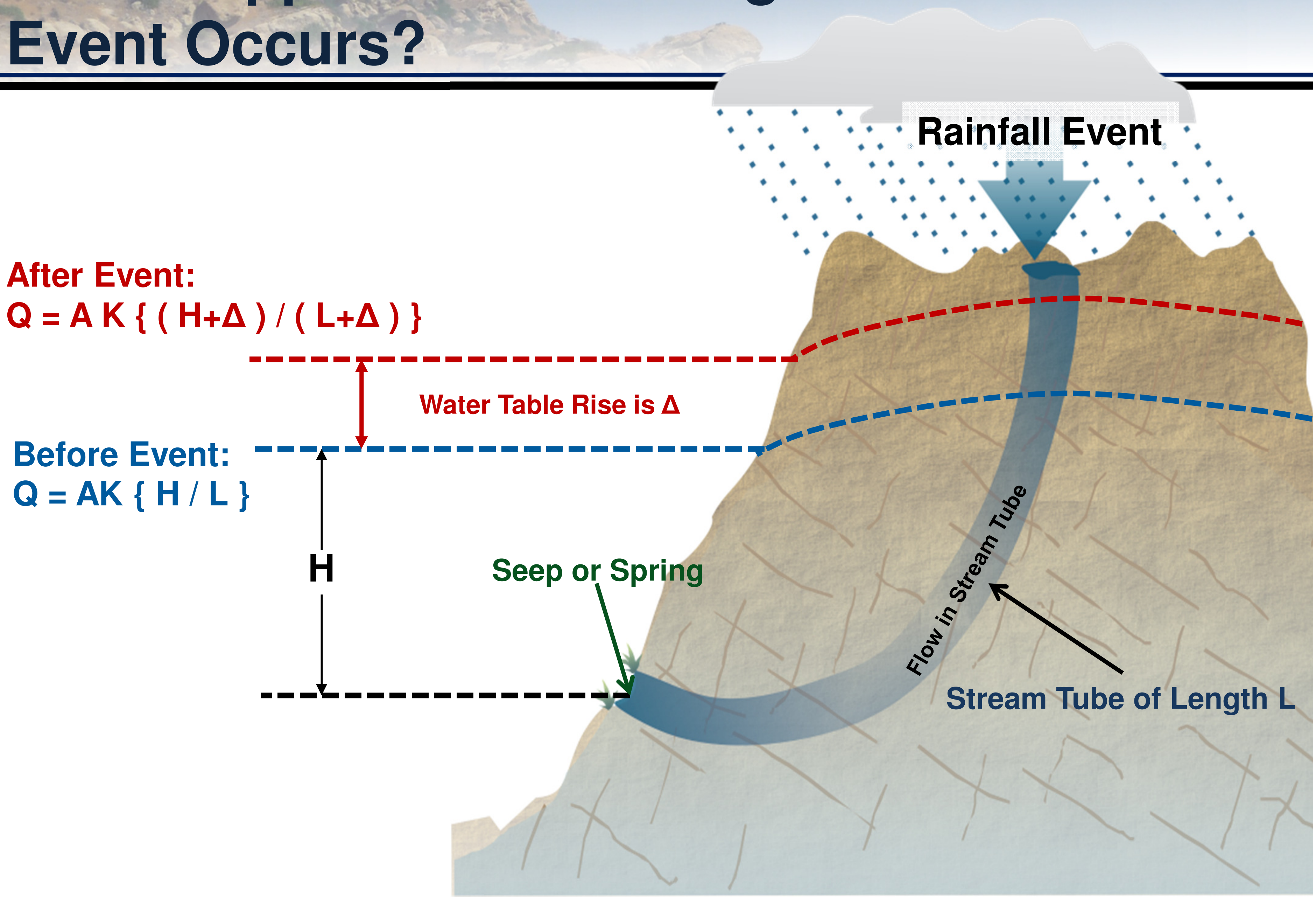
What Happens When A Big Rainfall Event Occurs?

How is groundwater stored?

How does groundwater flow occur?



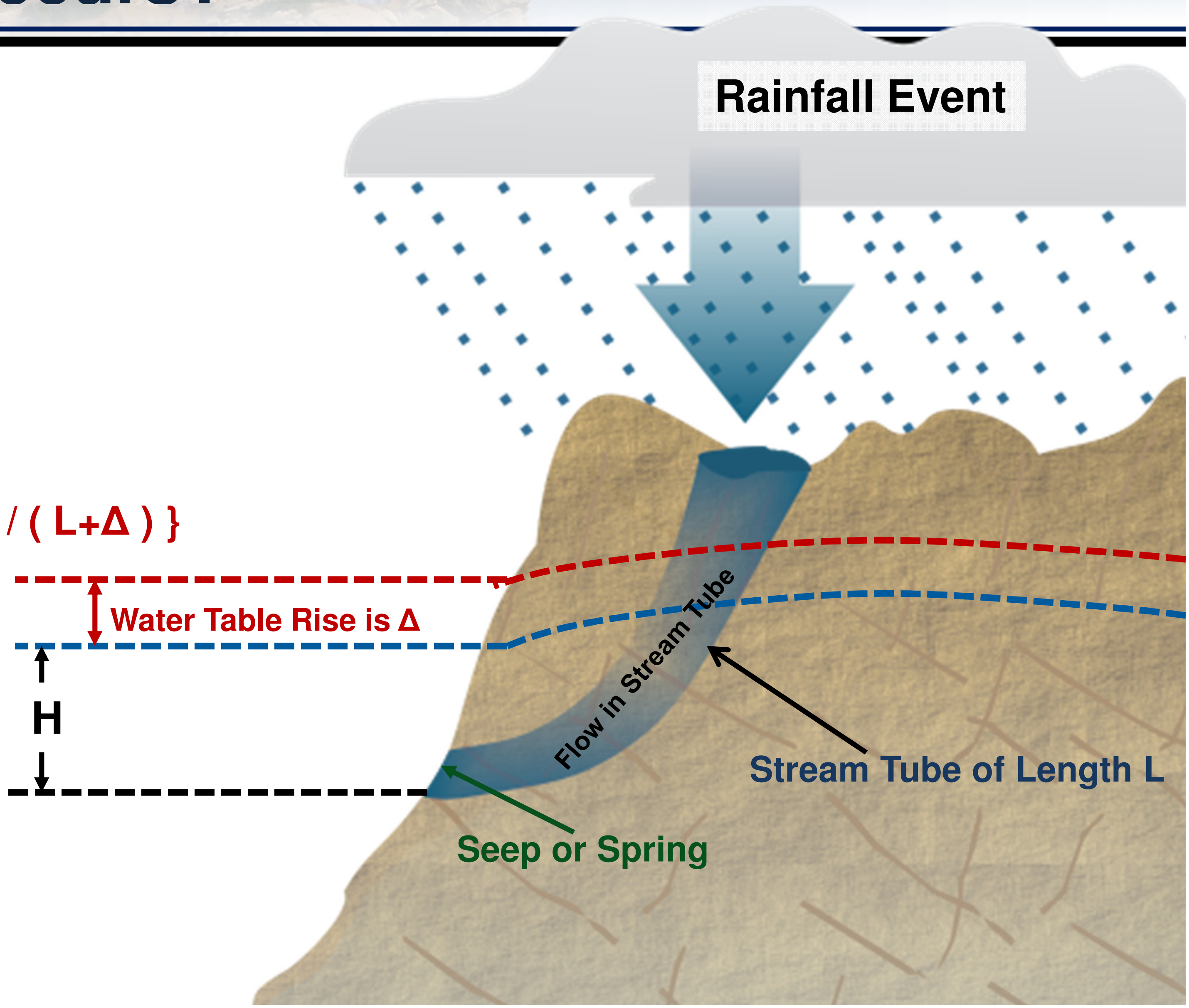
What Happens When A large Rainfall Event Occurs?



What Happens When A large Rainfall Event Occurs?

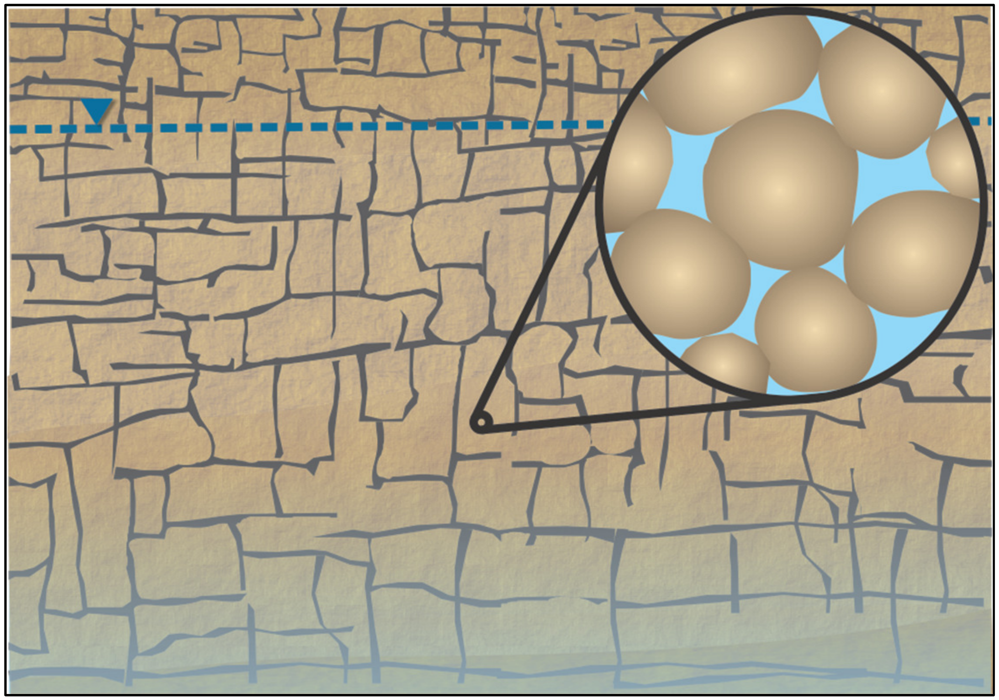
After Event:
$Q = A K \{ (H+\Delta) / (L+\Delta) \}$

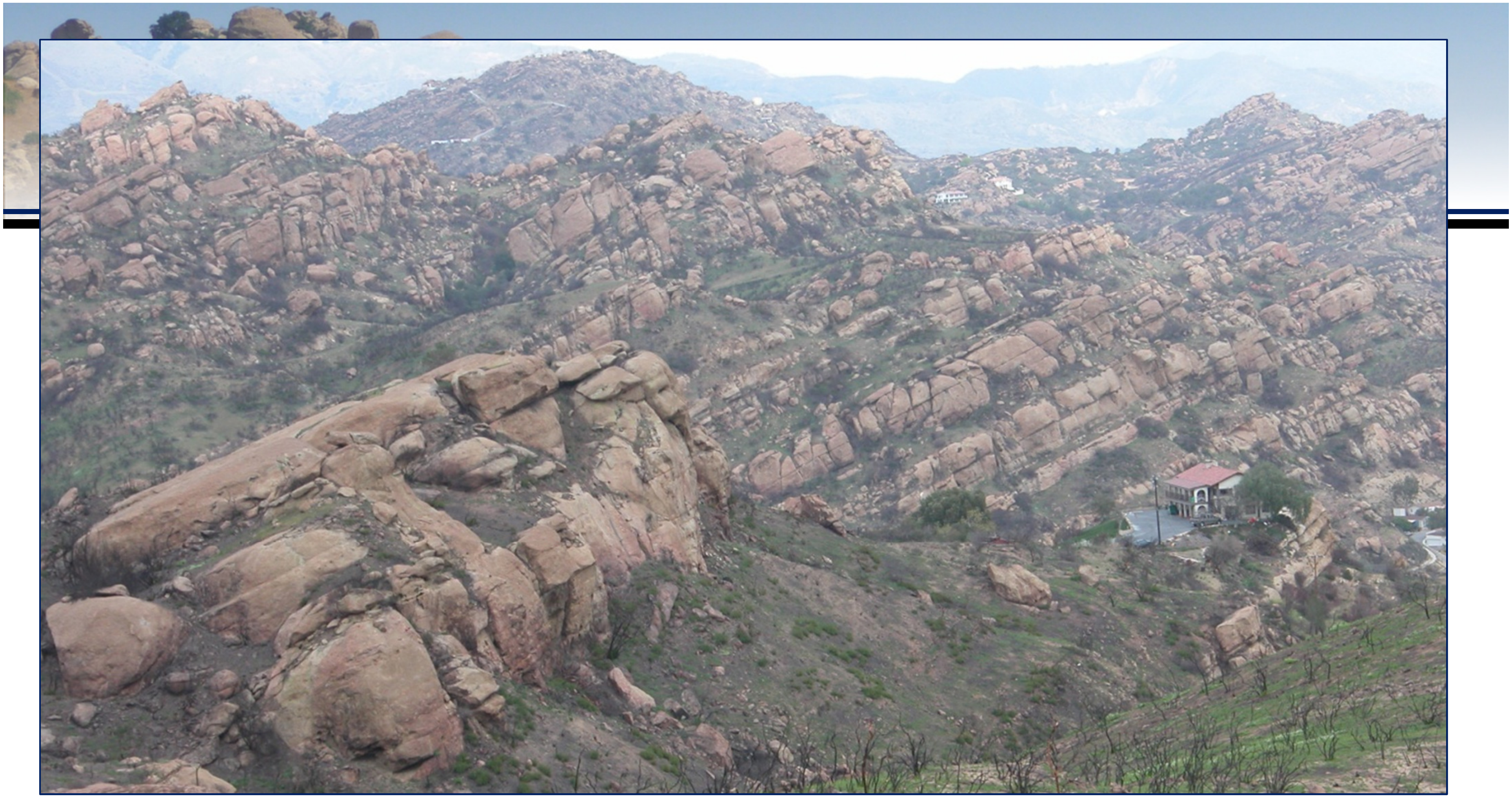
Before Event:
$Q = AK \{ H / L \}$



How Does Groundwater Occur?

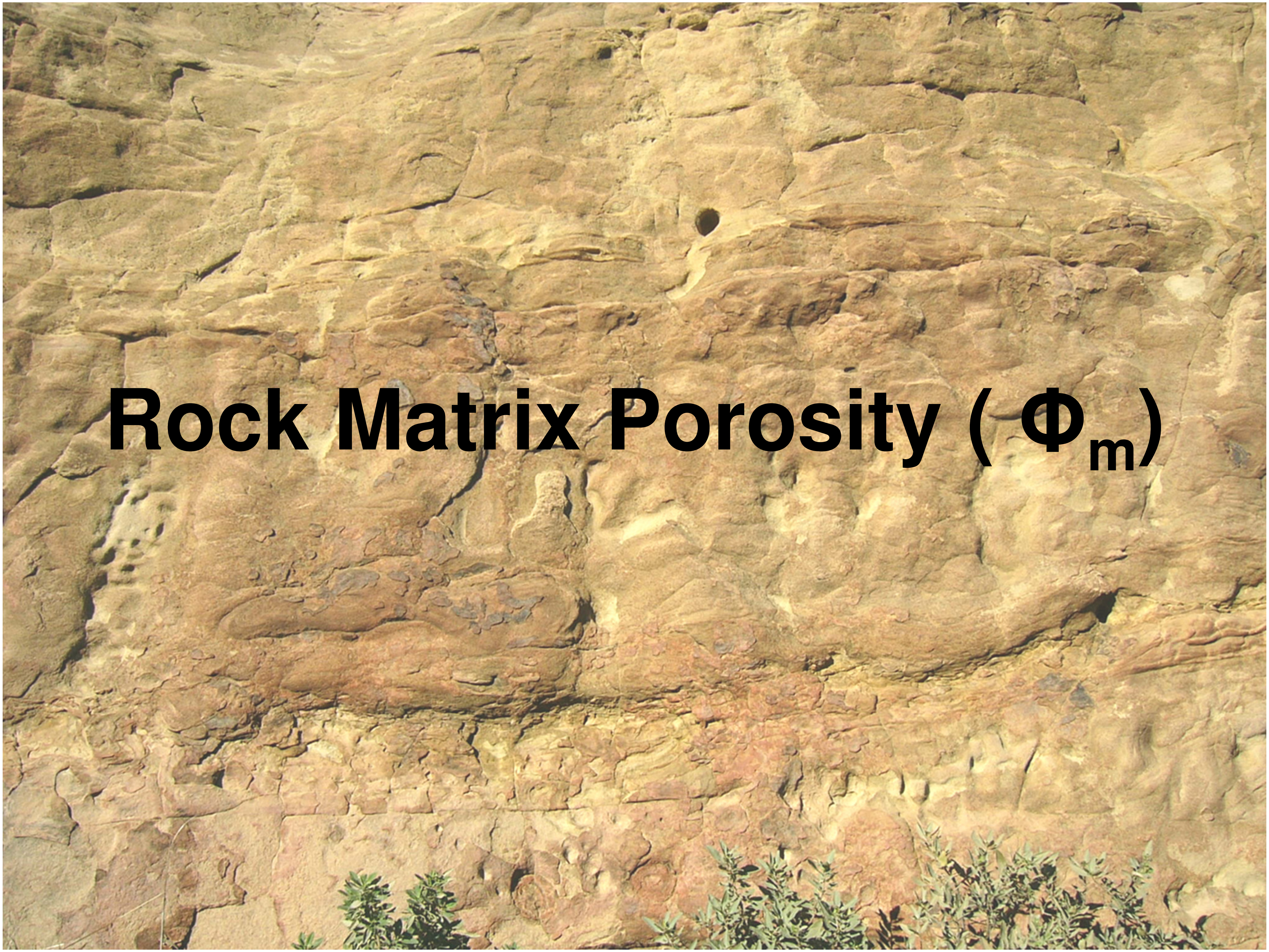
Practically all of the groundwater is present in the blocks of sandstone and shale between the fractures.



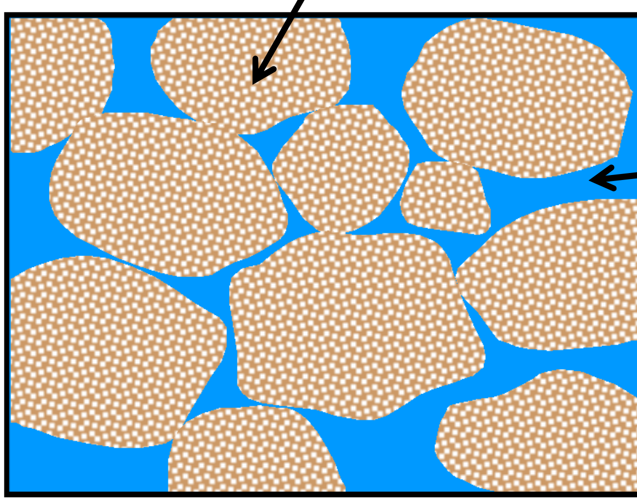


Matrix Blocks Are the Solid-Looking Sandstone Between the Fractures

Rock Matrix Porosity (Φ_m)



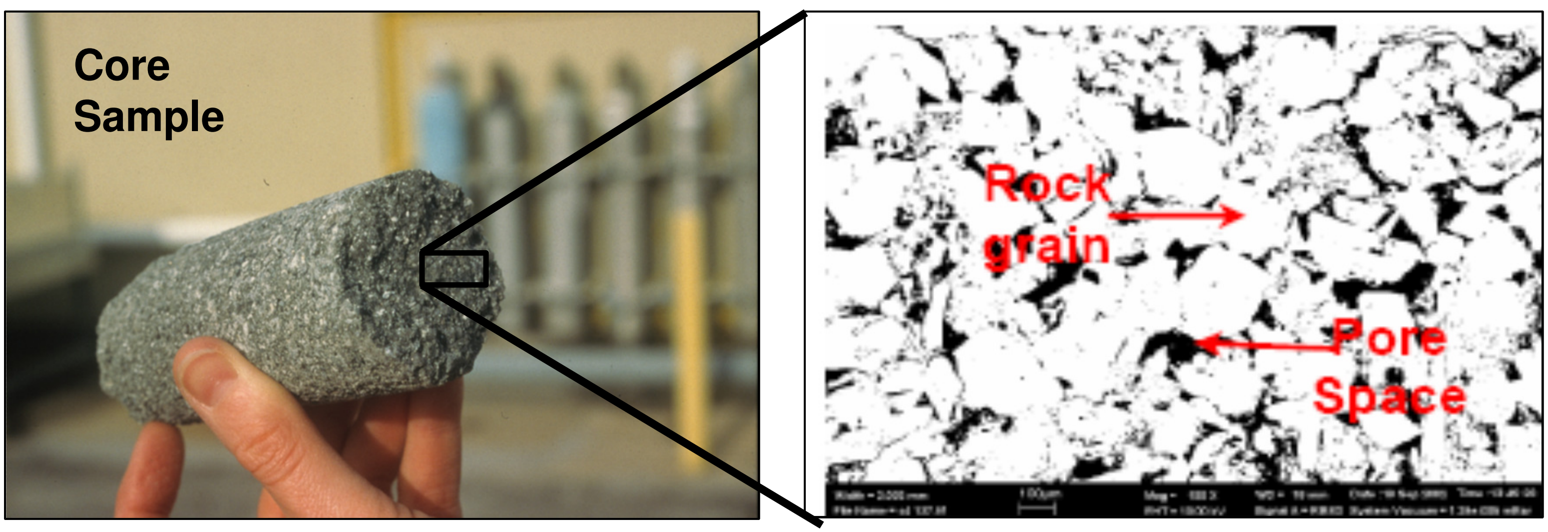
Rock Matrix Porosity



Microscopic View of Rock Matrix

$$\text{Matrix porosity } (\Phi_m) = \frac{\text{volume of inter granular voids}}{\text{total rock volume}}$$

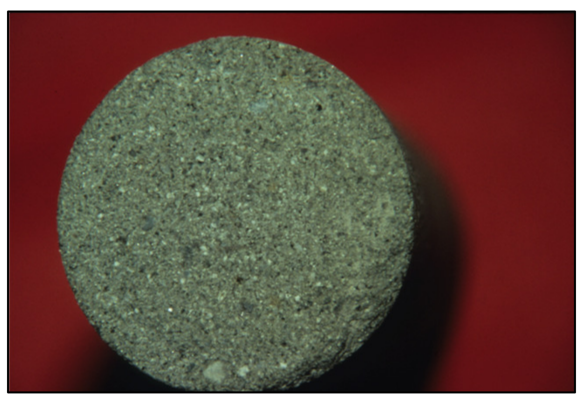
Porosity on Rock Core Sample

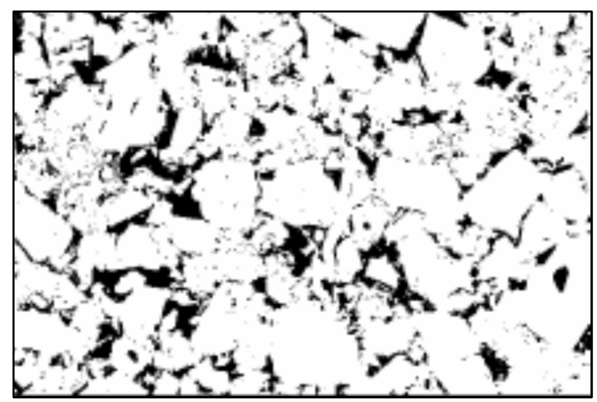


Matrix Porosity

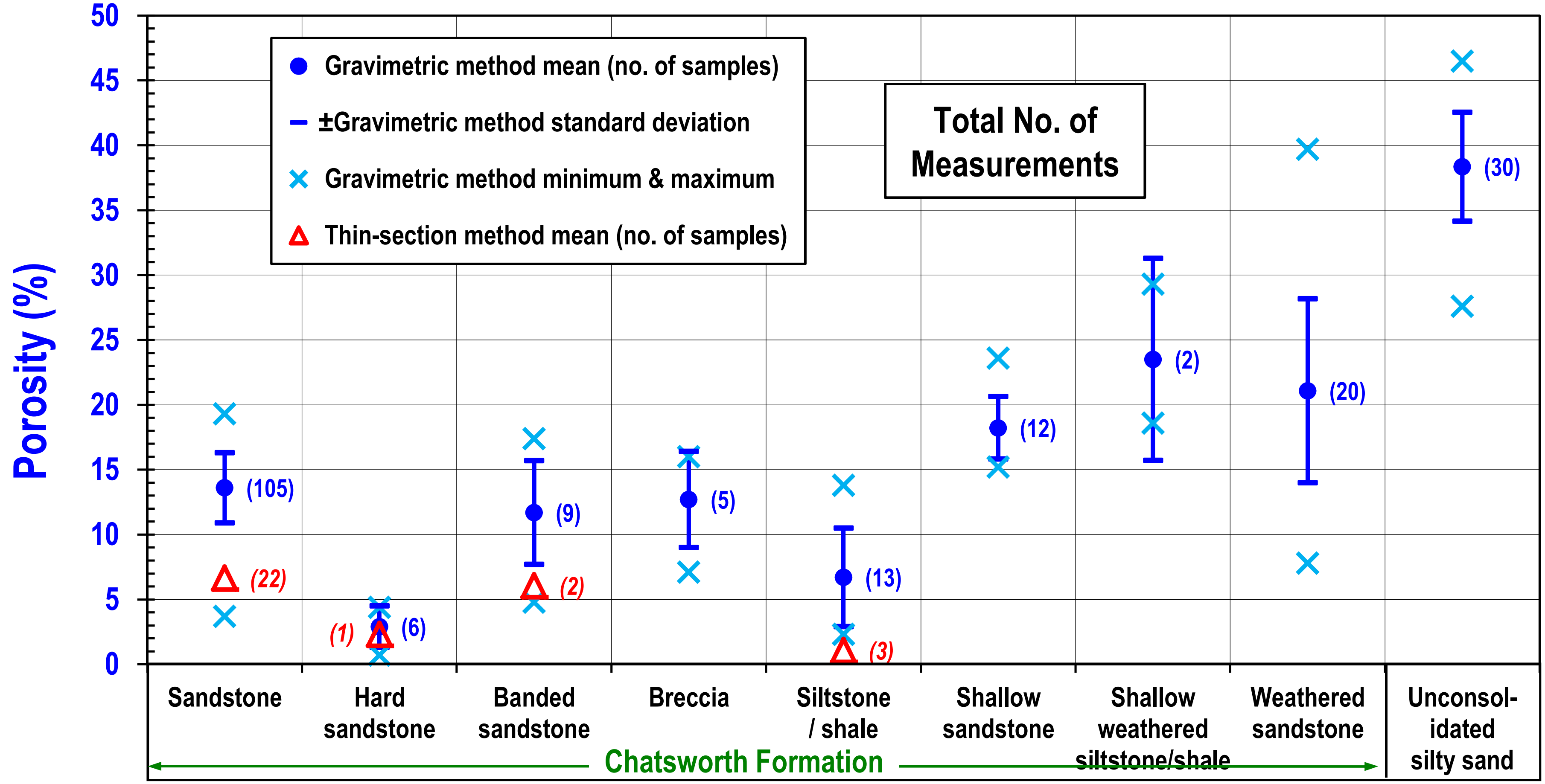
About 13 percent of the total rock volume is matrix void space.

$$\Phi_m = 0.13\ (13\%)$$





Core Sample Measurements: Matrix Porosity by Material Type and Method

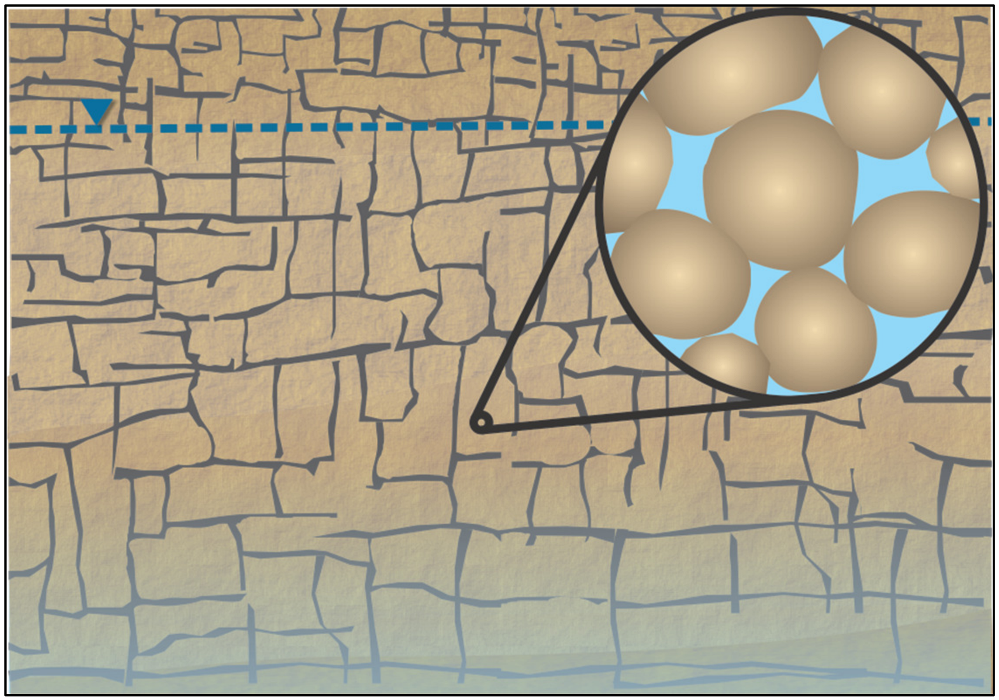


Santa Susana Field Laboratory, Ventura County, California
Chatsworth Formation

Source: Hurley et al., 2009

How Does Groundwater Occur?

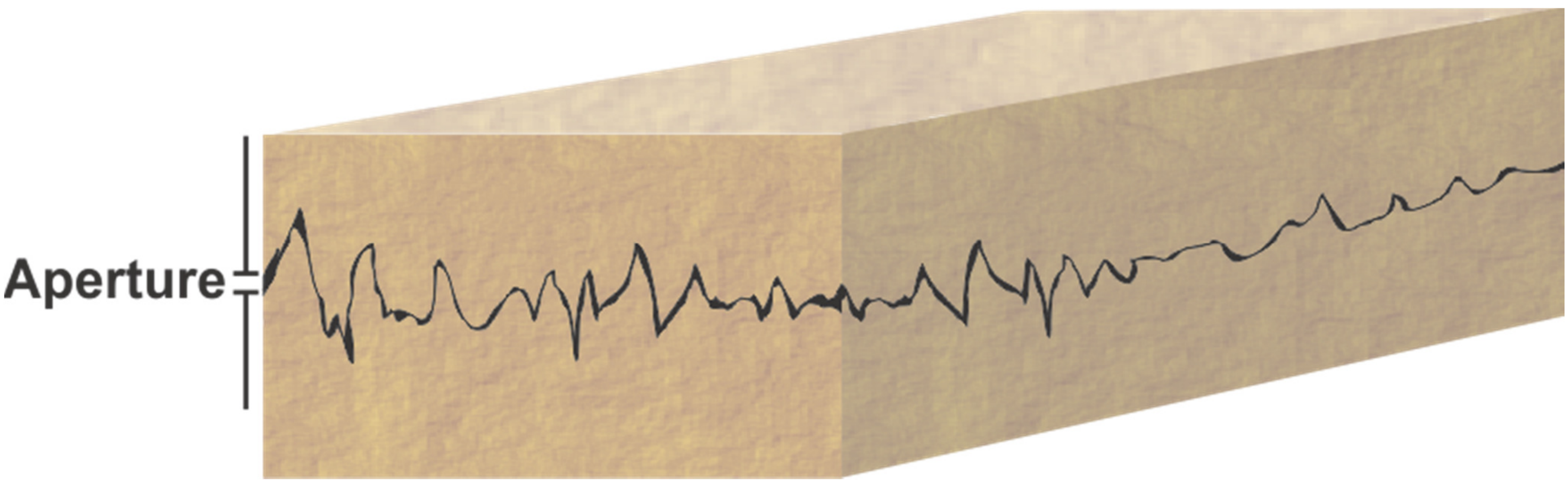
Practically all of the groundwater is present in the blocks of sandstone and shale between the fractures.



Interconnected Fracture Network

$$\text{bulk fracture porosity } (\Phi_f) = \frac{\text{volume of fracture voids}}{\text{total rock volume}}$$

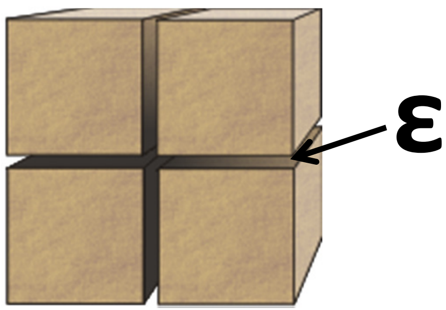
Variability in Fracture Aperture



Conceptualization of Bulk Fracture Porosity

For an aperture of 50 Microns

Cubic Matrix Blocks



Fracture Porosity = 3ε/L

Spacing - Meters	Fracture Porosity
1	0.00015
5	0.00003
10	0.000015

Tabular Matrix Blocks

Fracture Porosity = ε/L

Spacing - Meters	Fracture Porosity
1	0.00005
5	0.00001
10	0.000005

Below the water table:

Water fills both the matrix and fracture porosity

Groundwater present in matrix blocks:

13 percent of total rock volume

Groundwater present in fractures:

0.001 – 0.1 percent of total rock volume

Groundwater Flow

Groundwater flow is controlled by numerous, interconnected fractures.

Hydrogeologic Terminology

FRACTURE

- **A secondary permeability feature that renders a geologic unit more permeable.**
- **Any open elongated feature such as open crack, joint, fault or bedding plane**

Geologic Fractures

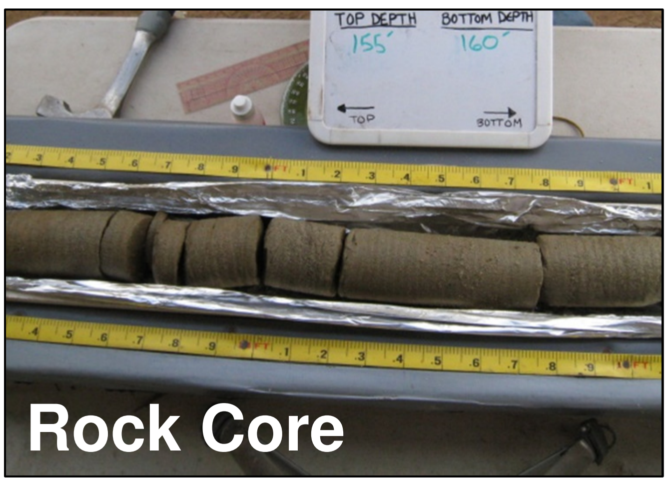
Structural Fractures:

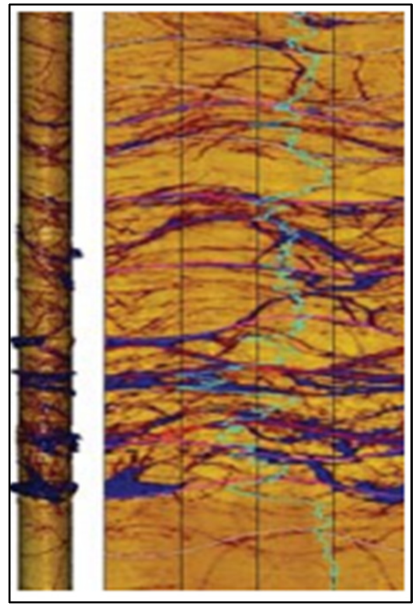
- Joint
- Fault
- Shear Zone
- Slip Plane

Sedimentary Features:

- Bedding Plane
- Parting

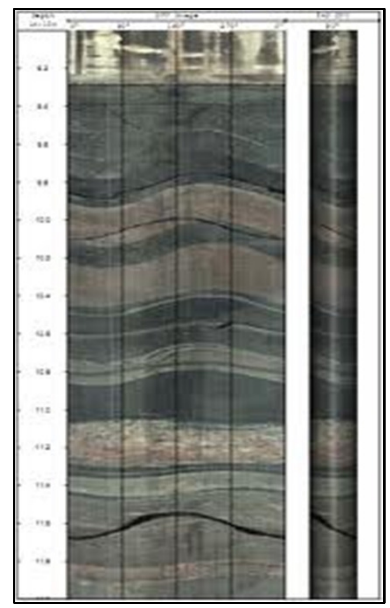
Visual Fracture Observations



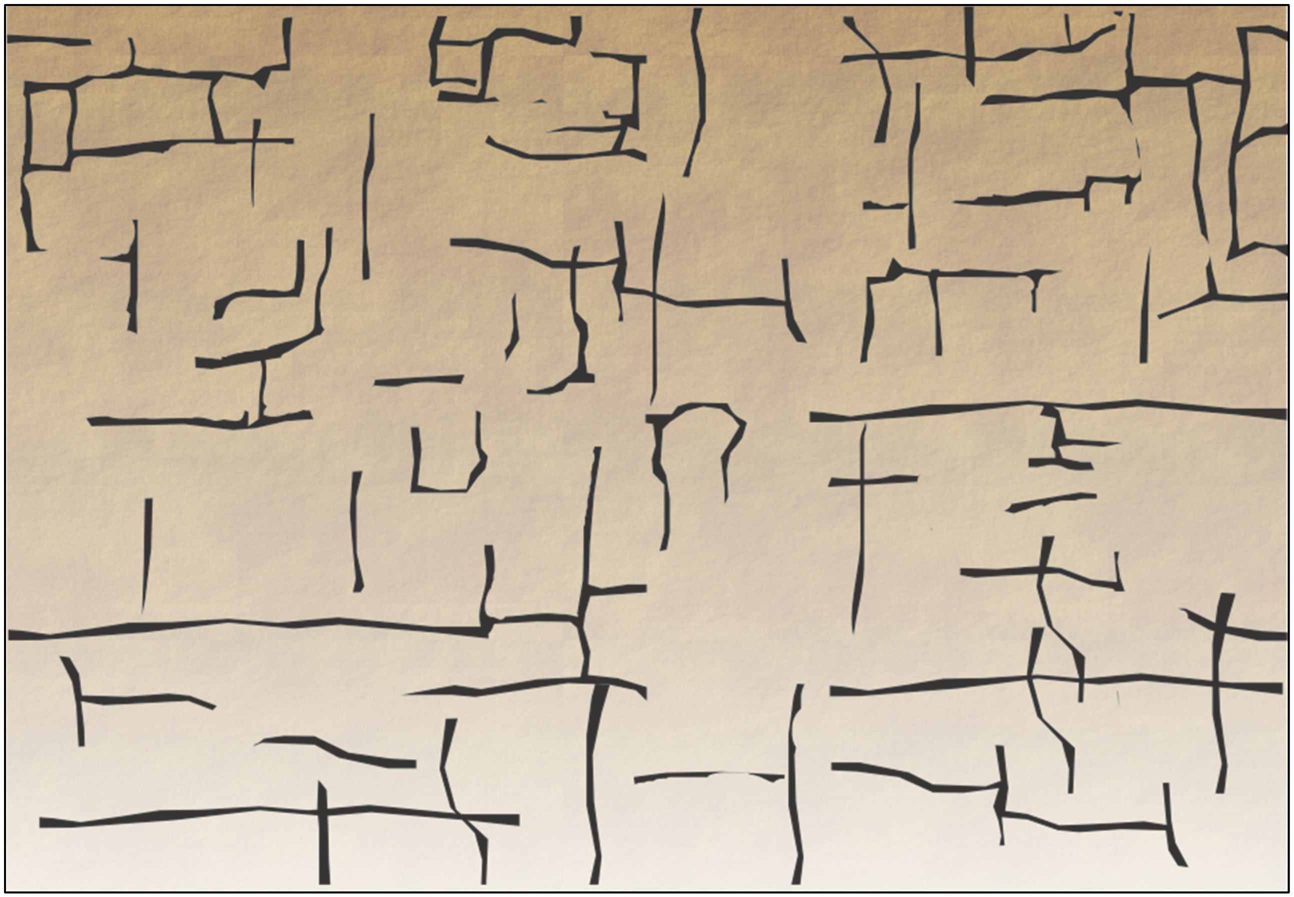


Acoustic Televiewer

Optical Televiewer



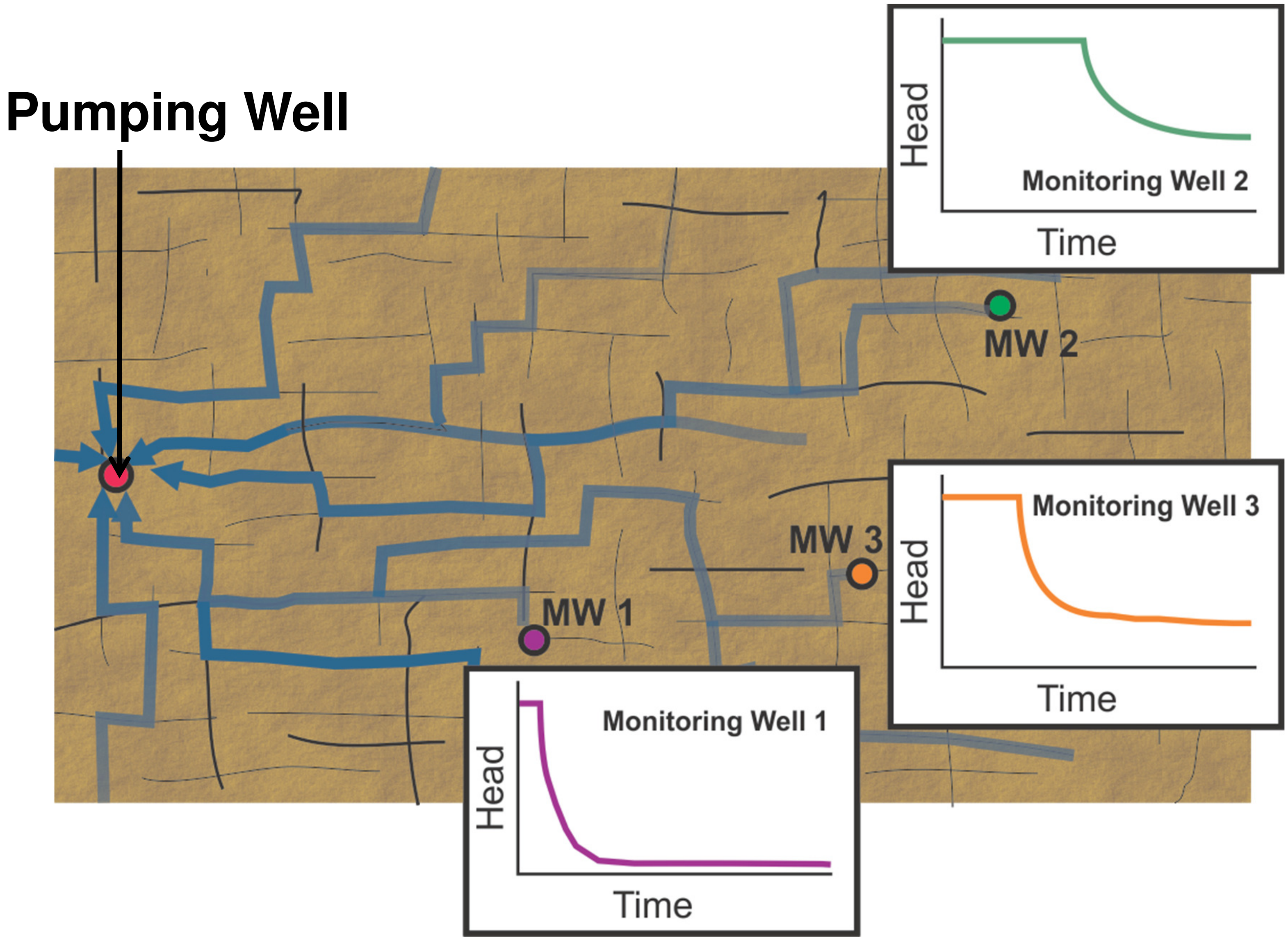
Sparse and Poorly Connected Network

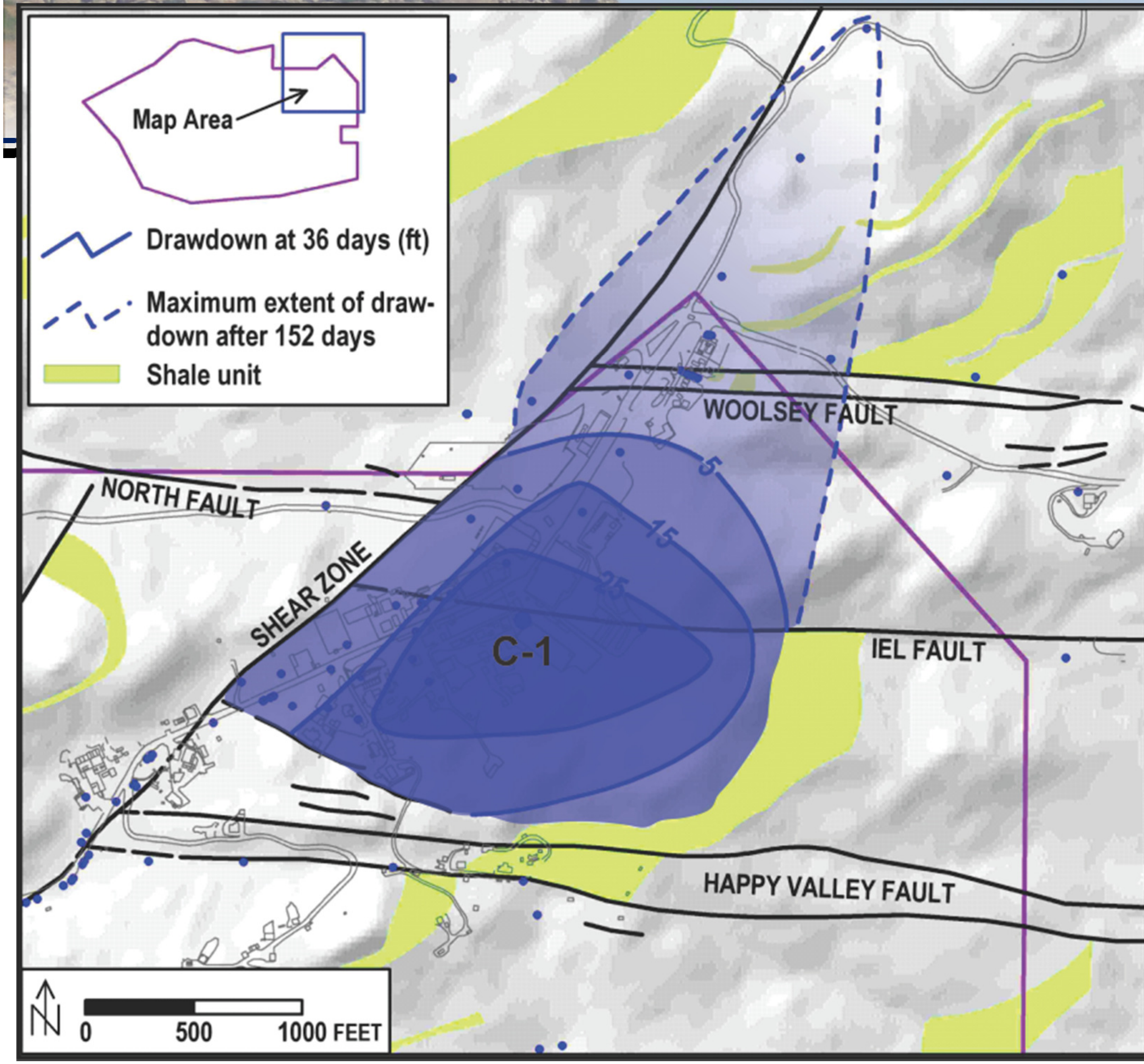


A Dense, Well Interconnected Network

Typical Fracture Density at SSFL = 2 to 3 per meter

Pumping test to determine fracture network connectivity





Long term Aquifer Test

Corehole C-1

-600 ft deep

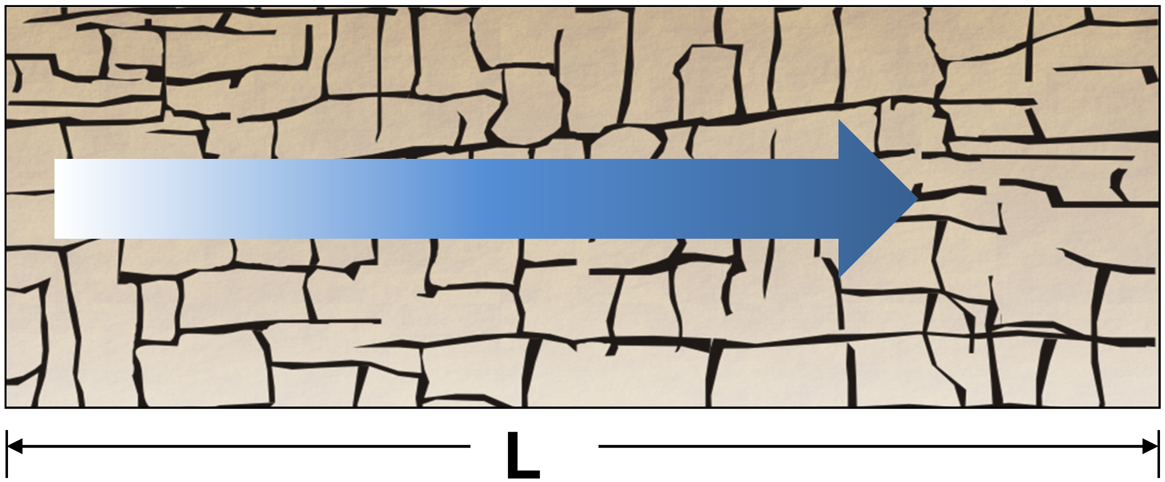
-Pumped at 40 gpm for 152 days

2003-04

Groundwater Flow Rates (Q) In A Fractured Porous Rock

K ~ Hydraulic Conductivity

Hydraulic Head h_1



Hydraulic Head h_2

In Rock Matrix

$Q_m = AK_m(h_1\text{-}h_2) / L$

K_m = matrix K
(Lab Measured)

In Fractures

$Q_f = AK_f(h_1\text{-}h_2) / L$

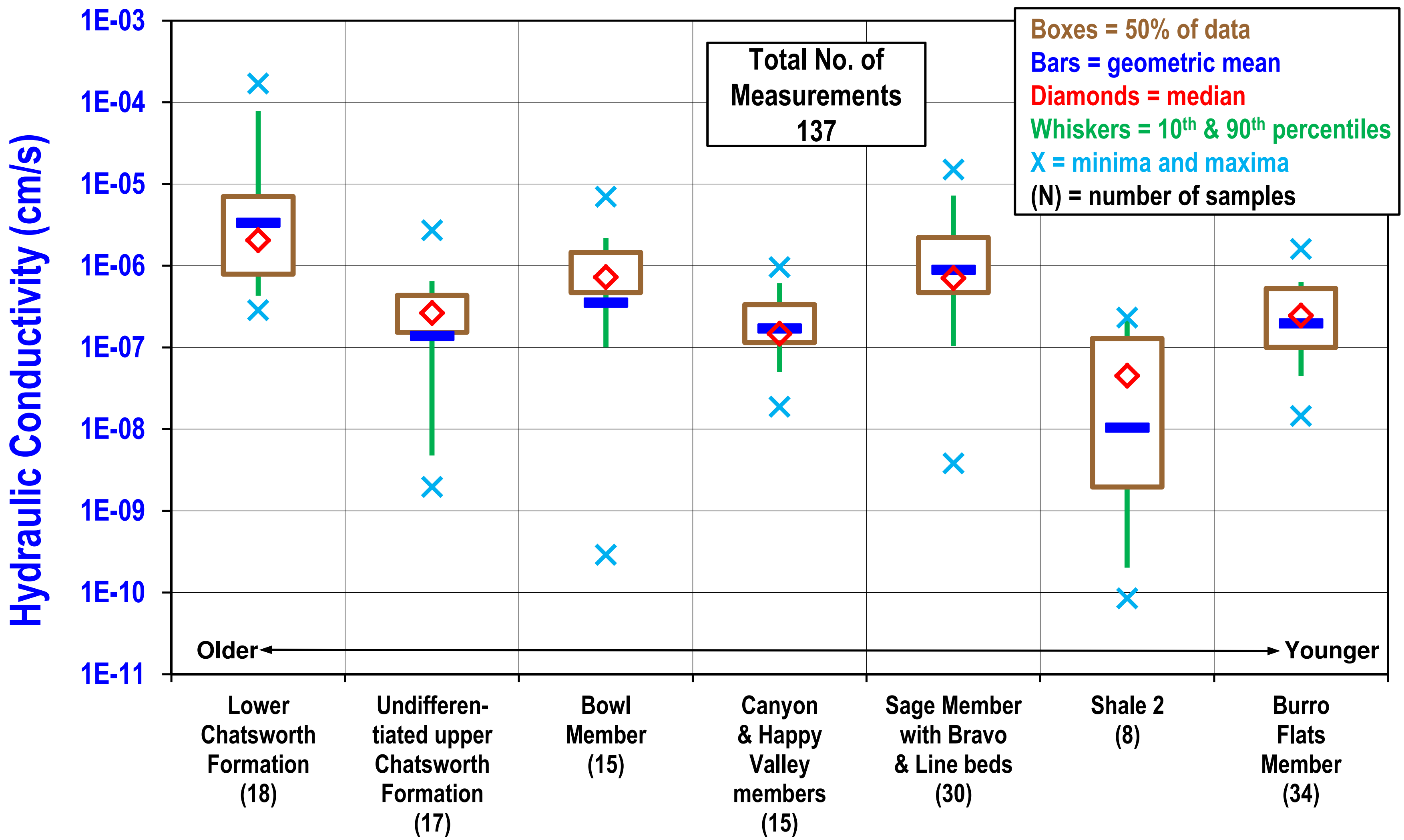
K_f = fracture K

In Both

$Q_b = AK_b(h_1\text{-}h_2) / L$

K_b = bulk K
(Field Measured)

Core Sample Measurements of Matrix Hydraulic Conductivity by Hydrogeologic Unit



Santa Susana Field Laboratory, Ventura County, California

Source: Hurley et al., 2009

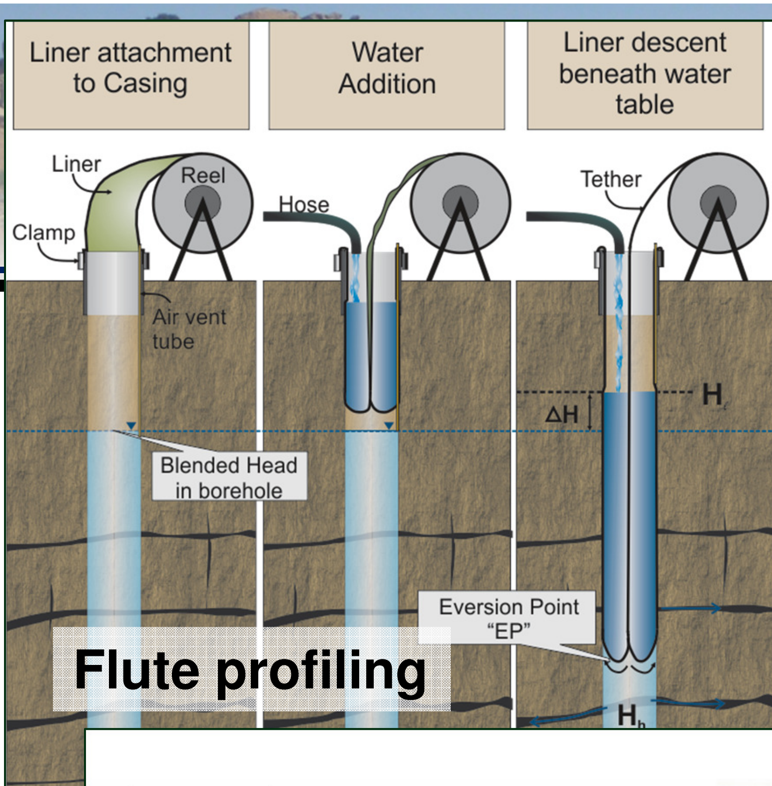
Types of Evidence for Permeable Fractures

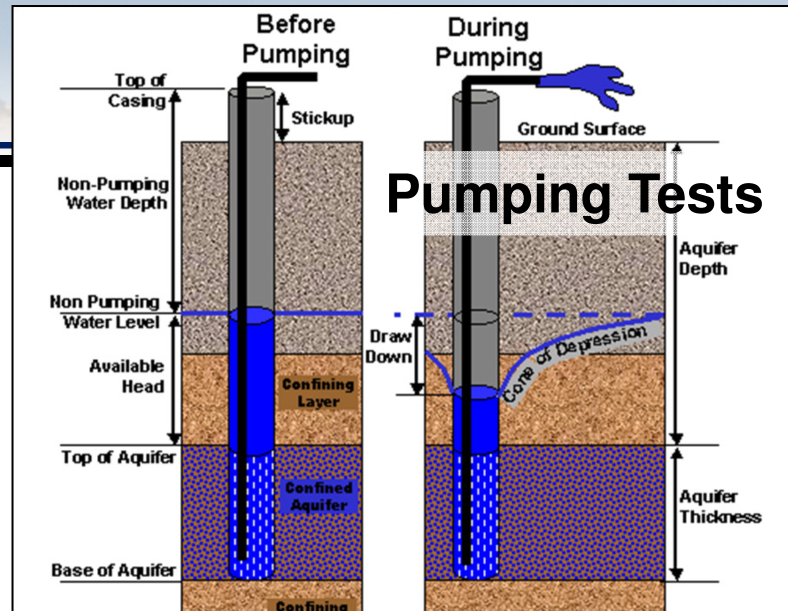
- **Hydraulic Tests in boreholes**
  - Using packers
  - Using Flexible Liners

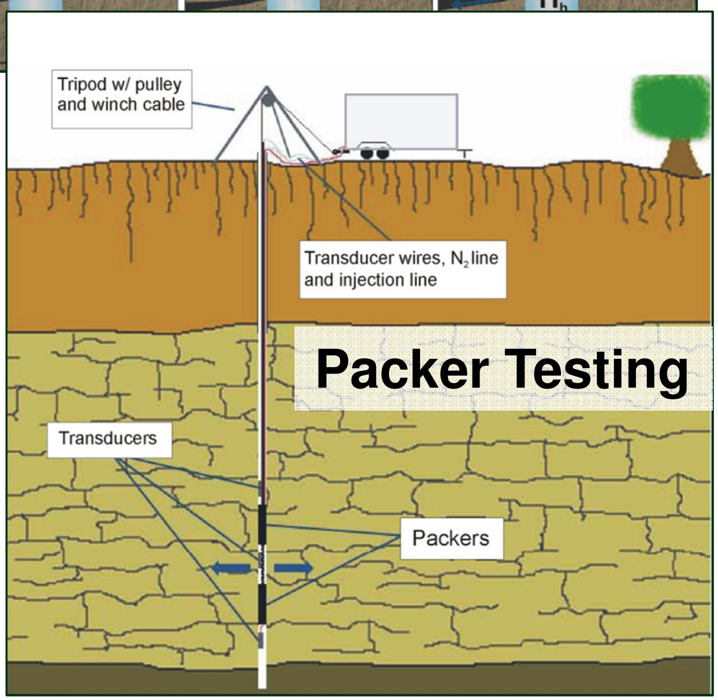
- **Large Scale pumping Tests**

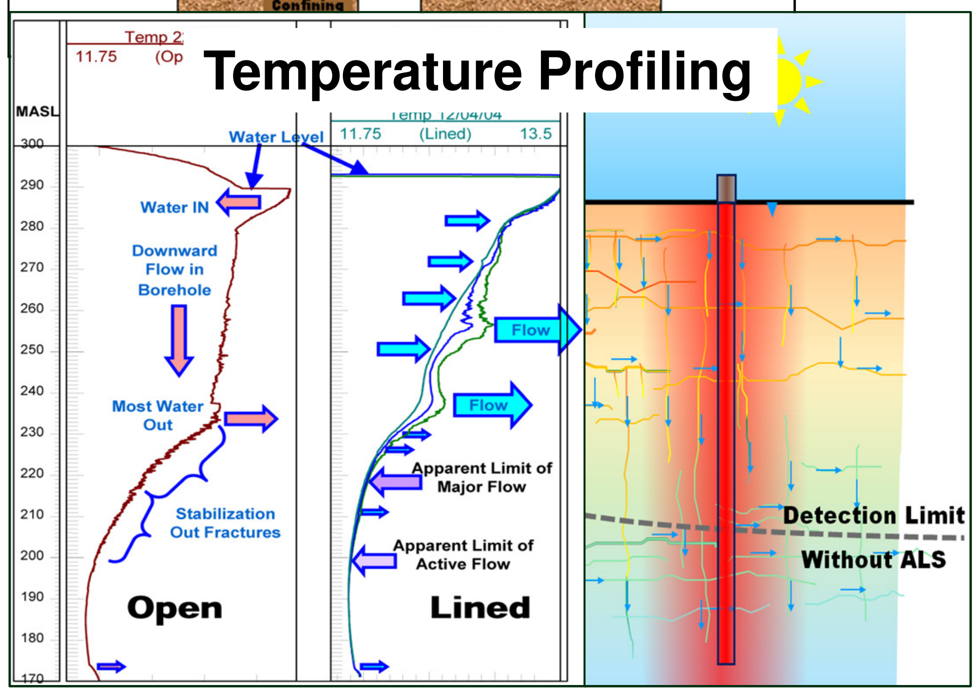
- **Temperature Profiling**

Evidence for Permeable Fractures

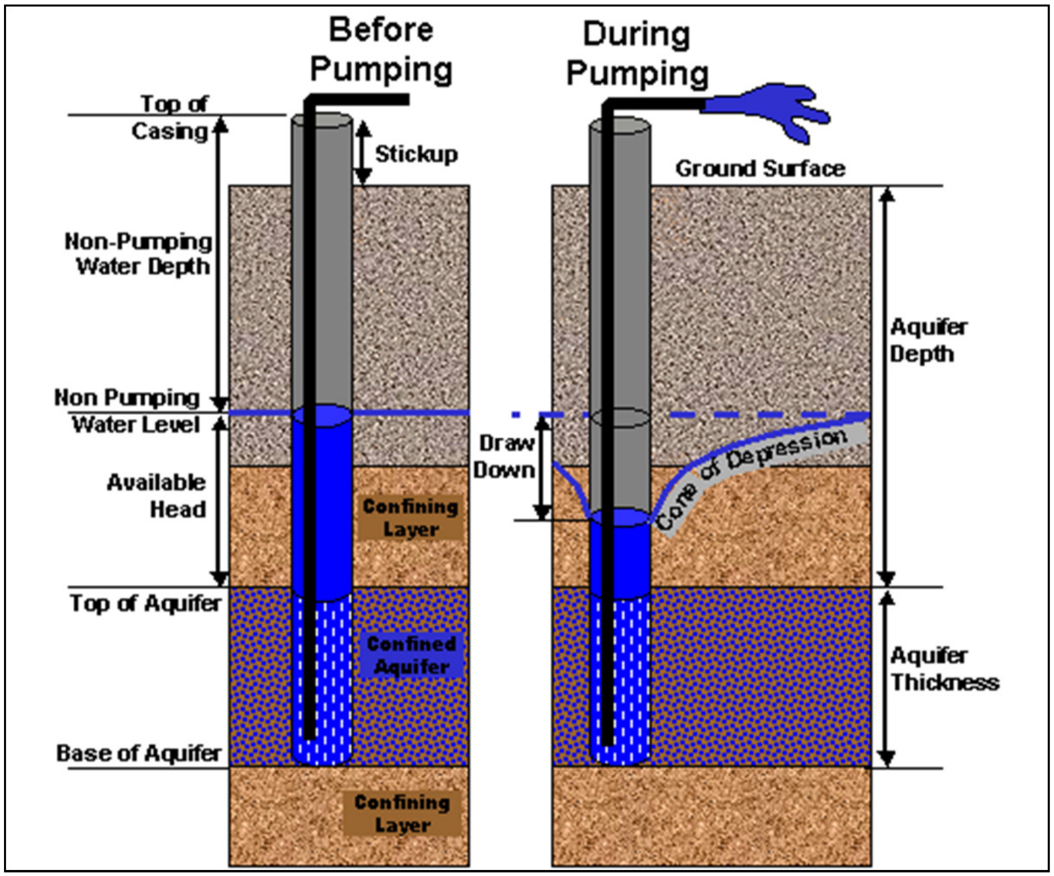


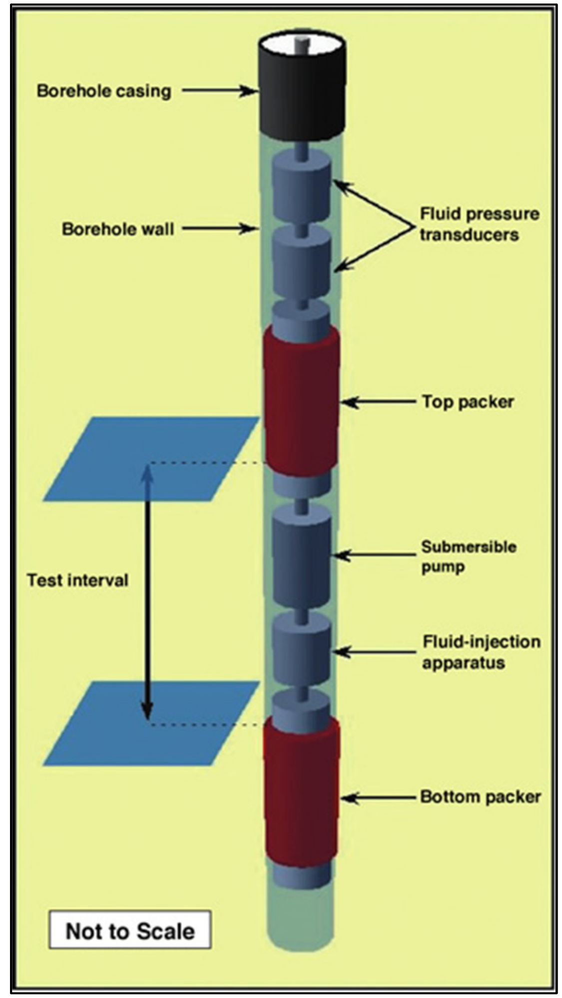






What is a hydraulic test?

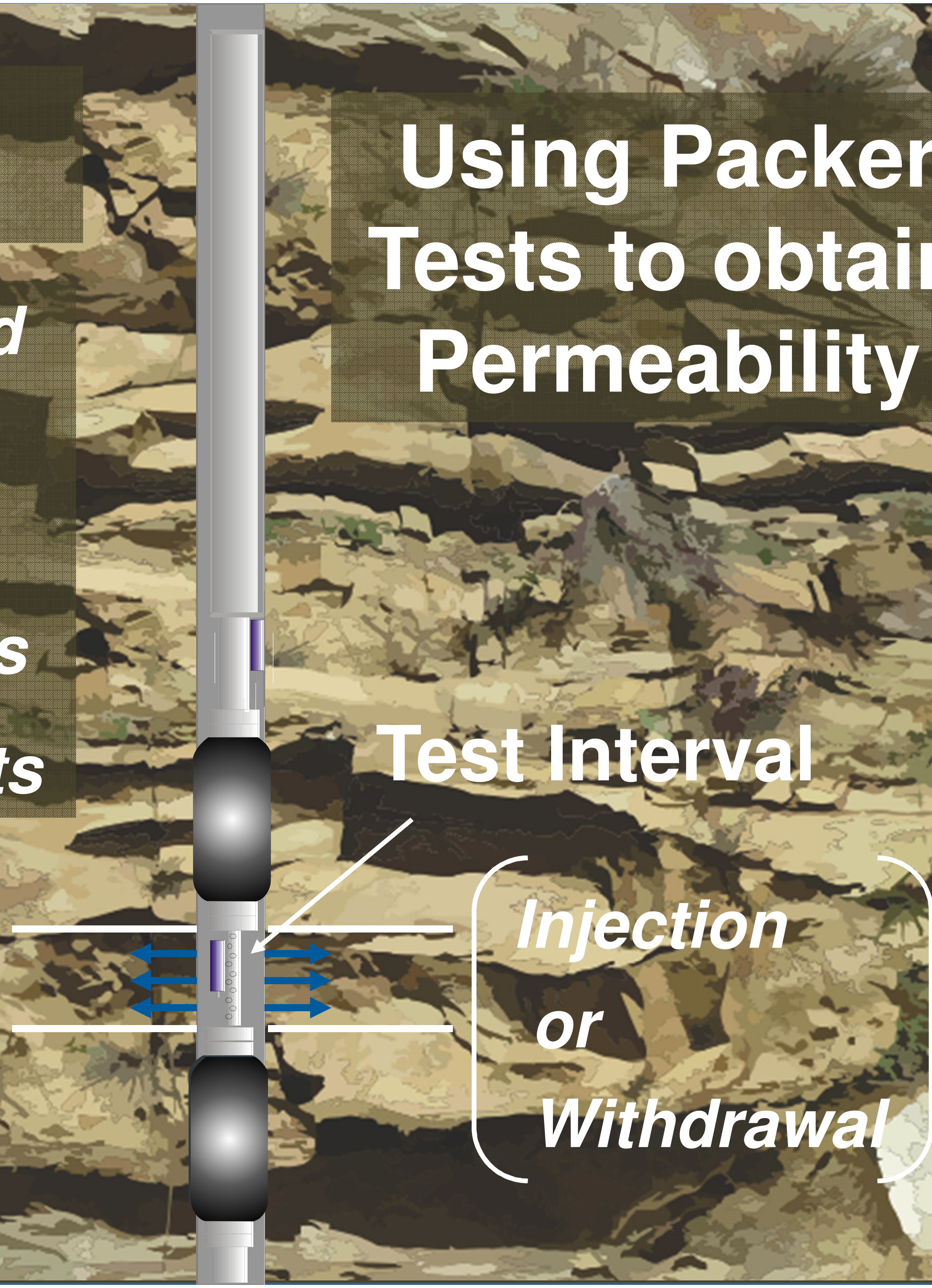




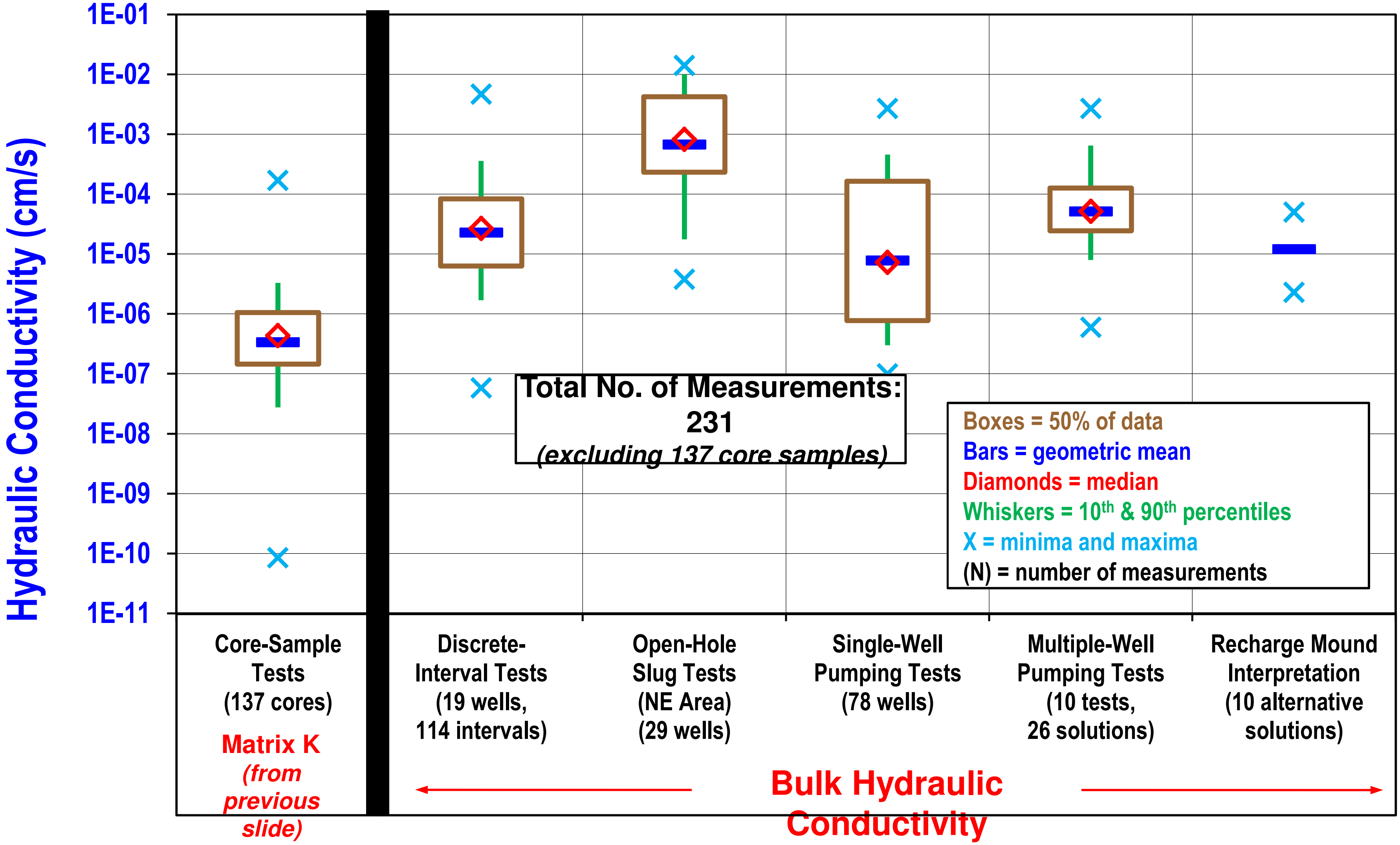
Four Types of Packer Tests

1. *Constant Head Step Tests*
2. *Slug Tests*
3. *Pumping Tests*
4. *Recovery Tests*

Using Packer Tests to obtain Permeability



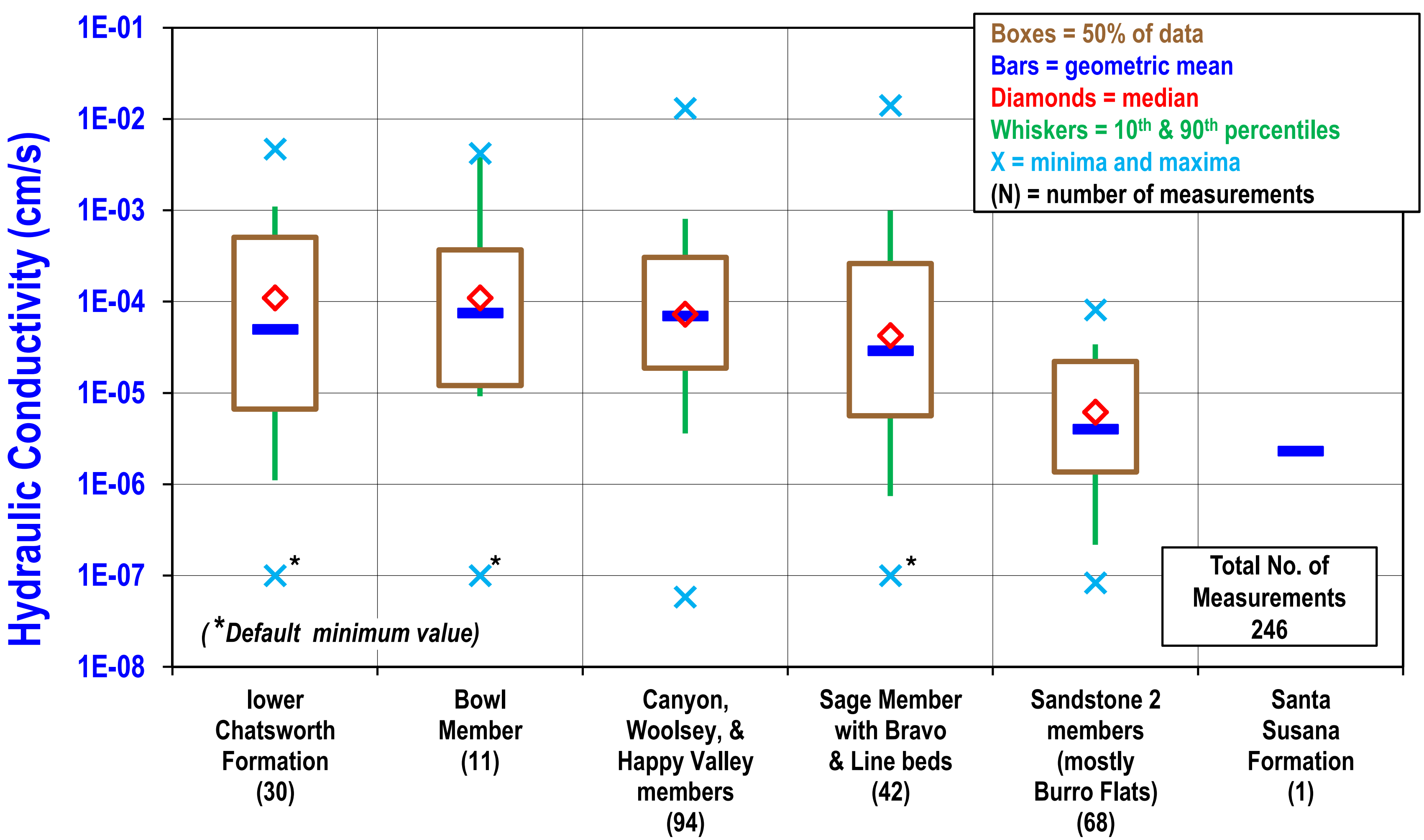
Estimates of Hydraulic Conductivity by Method of Measurement



Santa Susana Field Laboratory, Ventura County, California

Source: MWH, 2009

Estimates of Bulk Hydraulic Conductivity by Hydrogeologic Unit

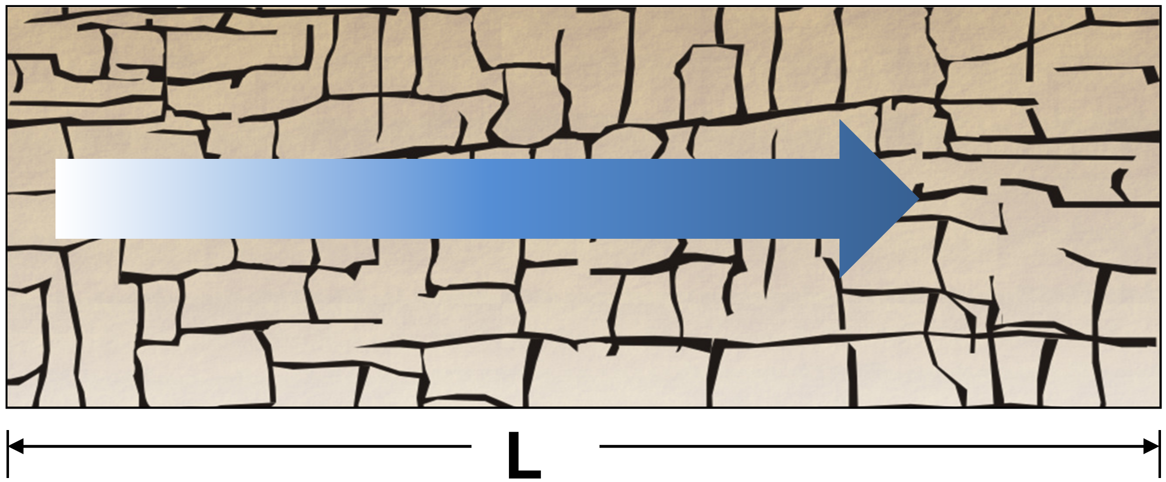


Source: MWH, 2009

Groundwater Flow Rates (Q) In A Fractured Porous Rock

K ~ Hydraulic Conductivity

Hydraulic Head h_1



Hydraulic Head h_2

In Rock Matrix

$Q_m = AK_m(h_1\text{-}h_2) / L$

K_m = matrix K (1E-6 cm/s)

In Fractures

$Q_f = AK_f(h_1\text{-}h_2) / L$

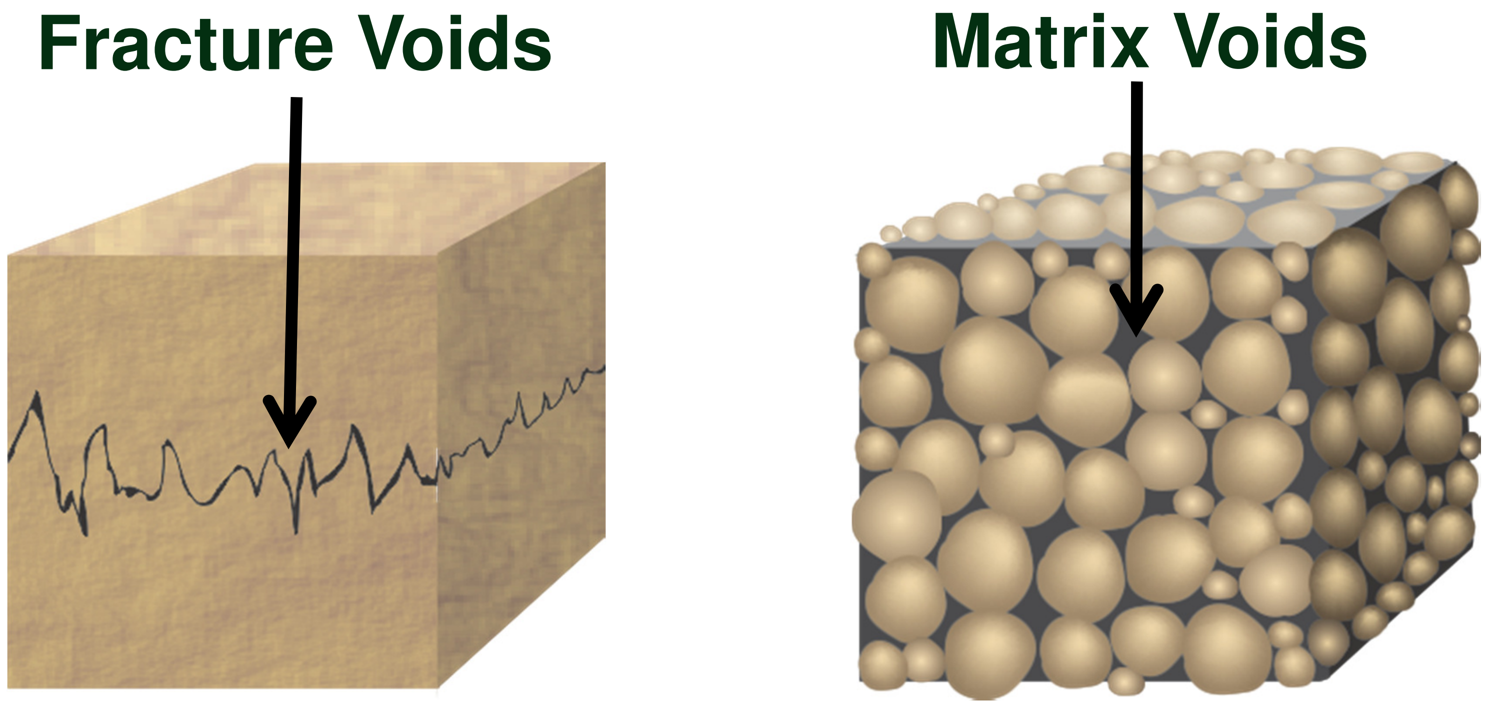
K_f = fracture K

In Both

$Q_b = AK_b(h_1\text{-}h_2) / L$

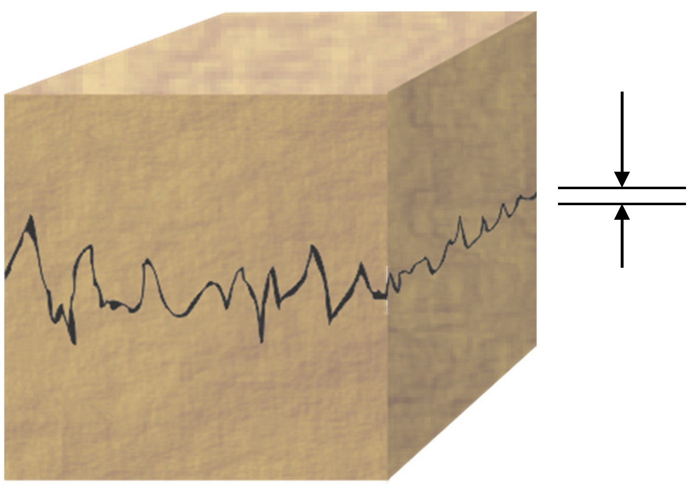
K_b = bulk K (5E-5 cm/s)

Groundwater flows most easily in the larger voids created by interconnected fractures



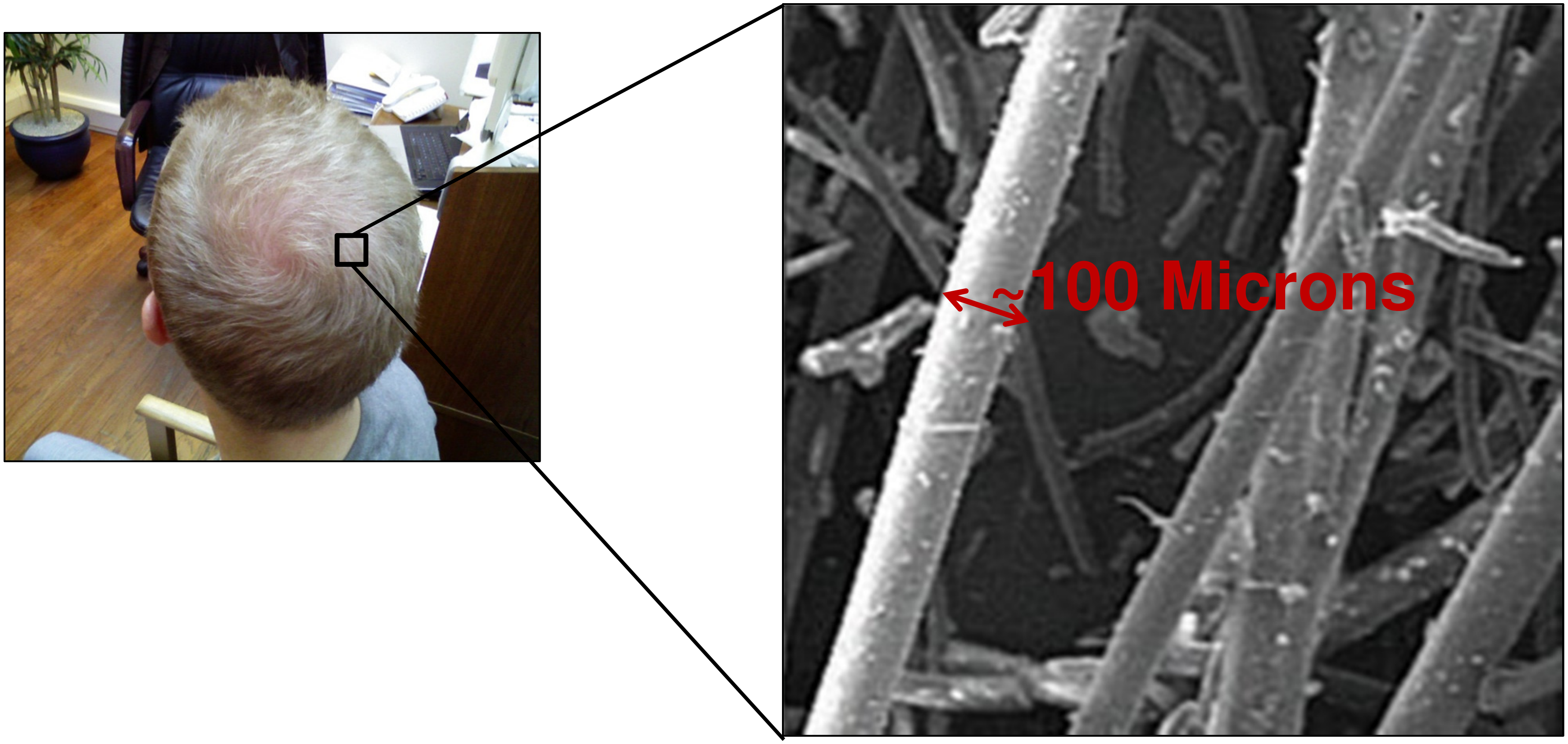
How is the size of fracture voids characterized?

The open distance between fracture walls.



Aperture

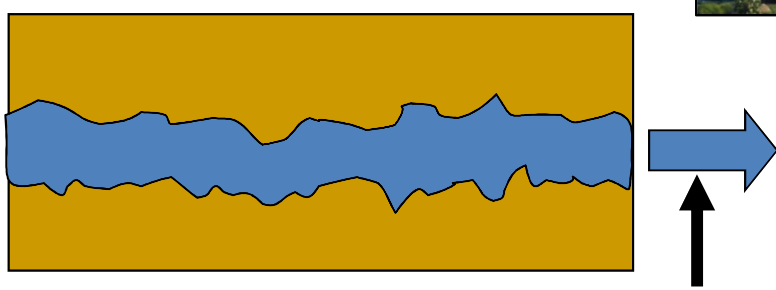
Aperture Size Concepts



1 micron = 1/1000 millimeters

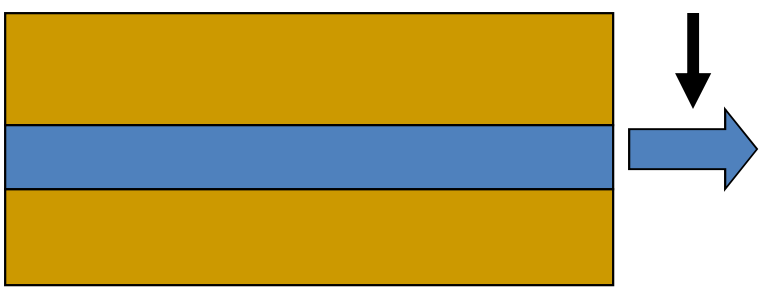
1 micron = 3.9 10^{-5} inches

Concept of Hydraulic Aperture



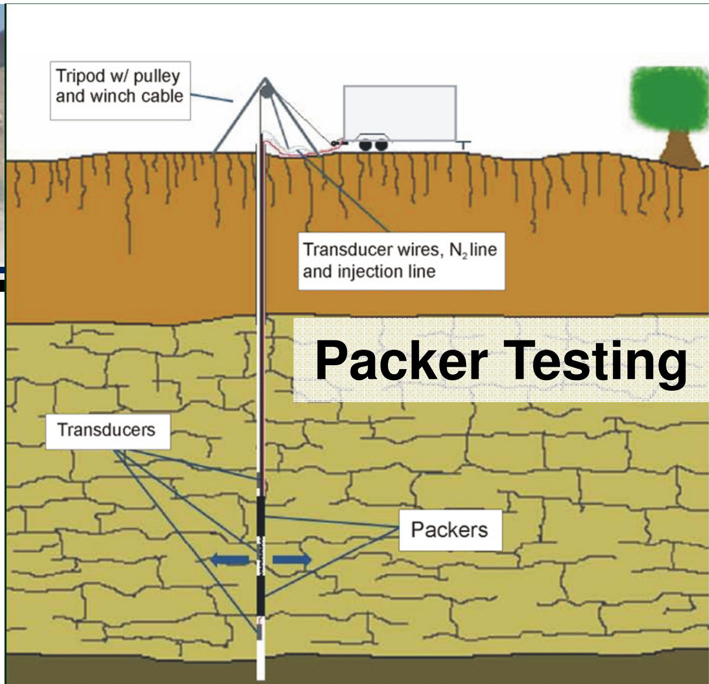
Rough-Walled Fracture (Variable Aperture)

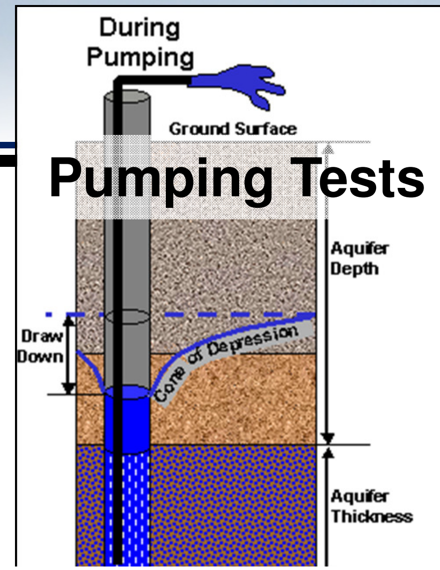
Same Flow Rate

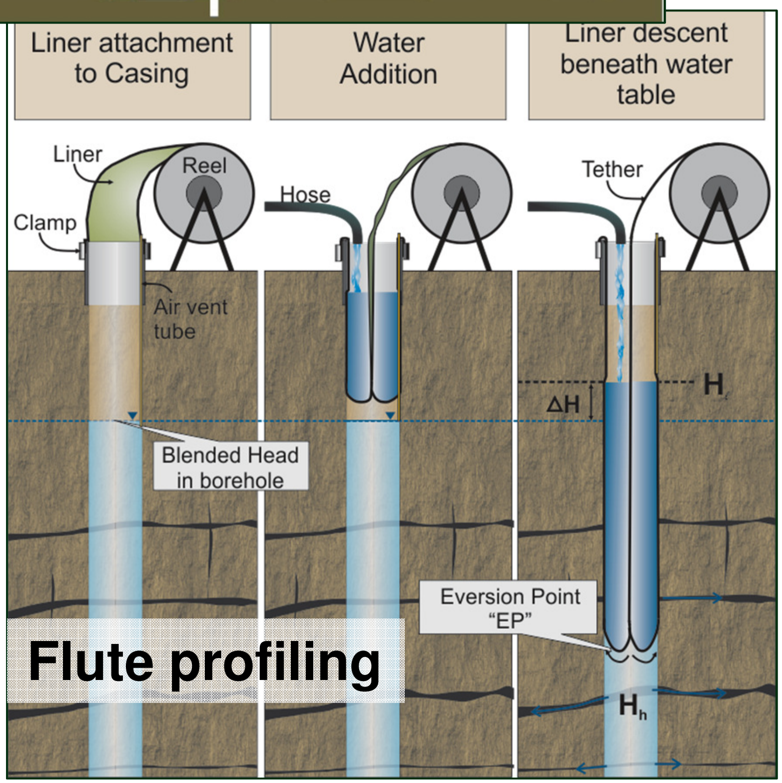


Smooth-Walled Fracture That Produces Same Flow Rate (Hydraulic Aperture)

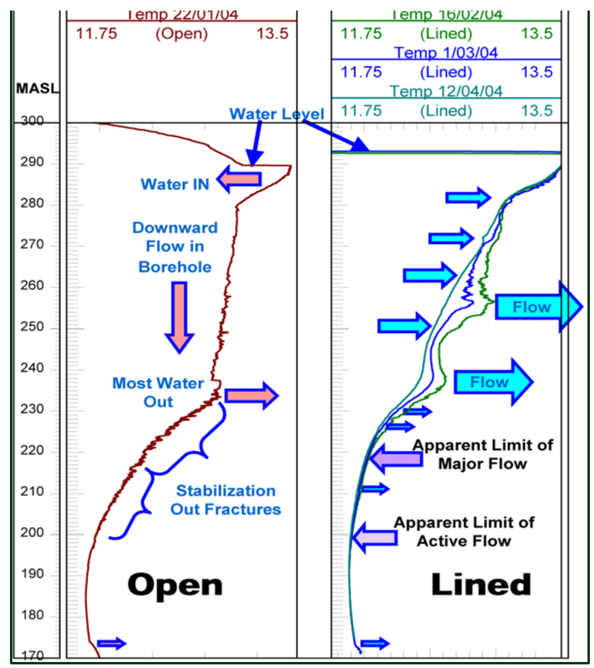
Evidence for Permeable Fractures







Temperature Profiling



Typical Values for Hydraulic Apertures at SSFL

Over 900 determinations of hydraulic aperture:

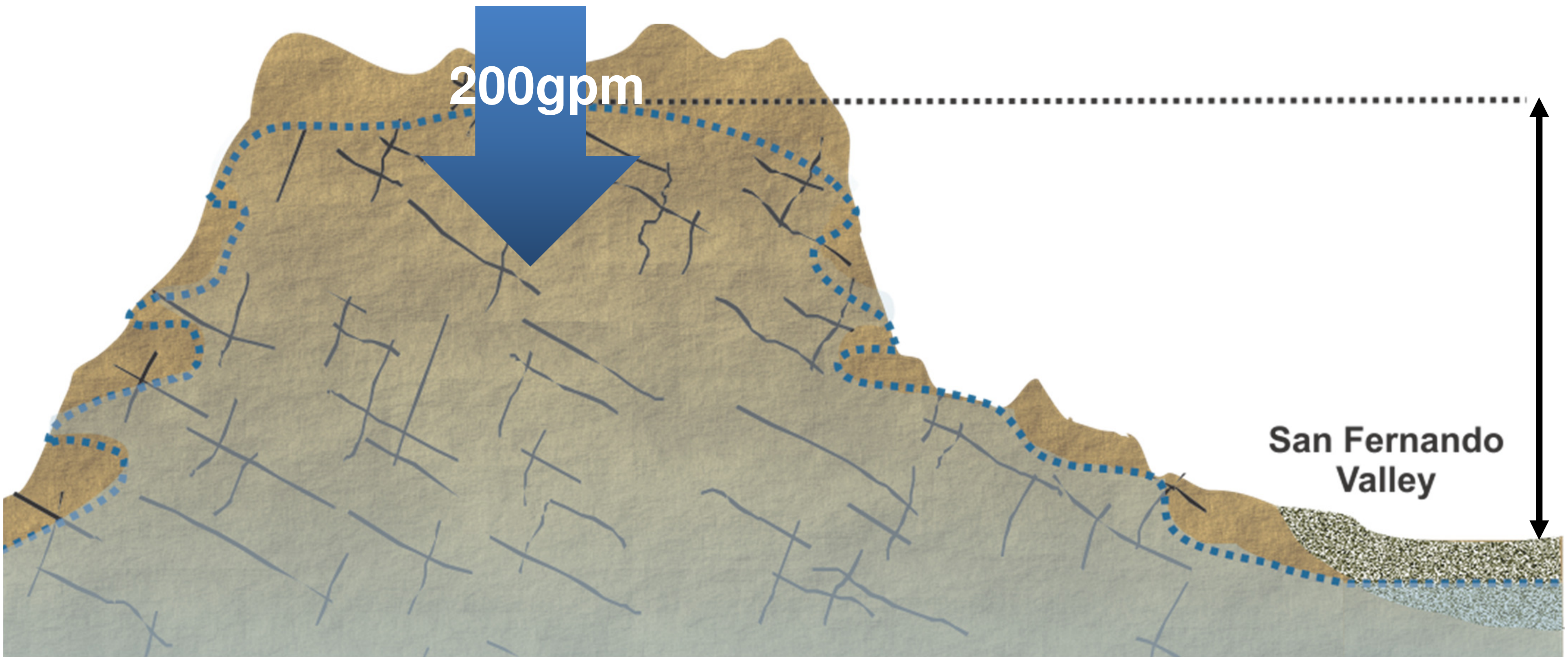
Typical: 70 to 100 microns

Range : 10 to over 1000 microns

Summary

Resistance to groundwater flow is substantial:

Groundwater mound stands 100's of feet above surrounding valleys with only about 200 gpm of recharge.



Summary

Some groundwater discharges to seeps on hill slopes:

More than 100 seeps and phreatophyte areas have been identified off site.




Summary

Volume water entering/leaving site is small:

Recharge = discharge ~ 200 gallon per minute

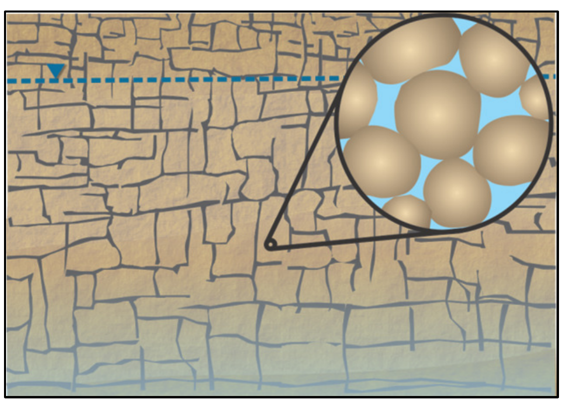
= 5 gpm

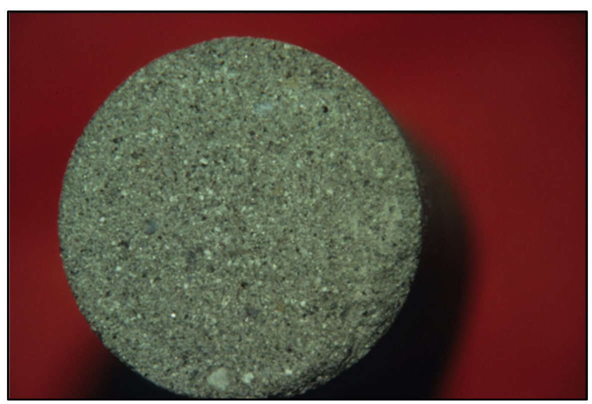
Summary

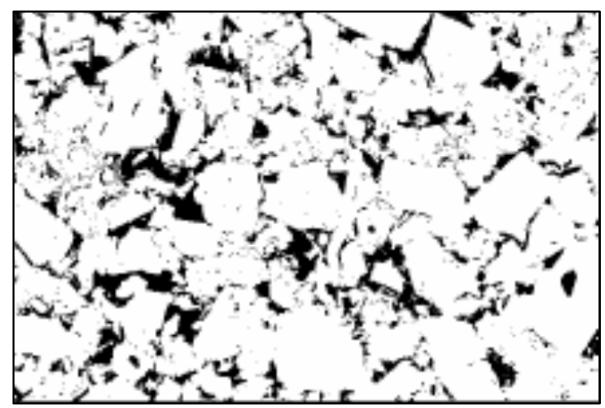
Virtually all the groundwater occurs in the matrix:

Matrix voids ~ 13 percent of rock volume

Fracture voids ~ 0.01 percent of rock volume







Summary

Flow is dominated by inter-connected fractures:

Matrix hydraulic conductivity ~ 1E-6 cm/s

Fracture hydraulic conductivity ~ 5E-5 cm/s


THANK YOU