Pumping induced land subsidence: A three-dimensional problem

Dr. Thomas J. Burbey

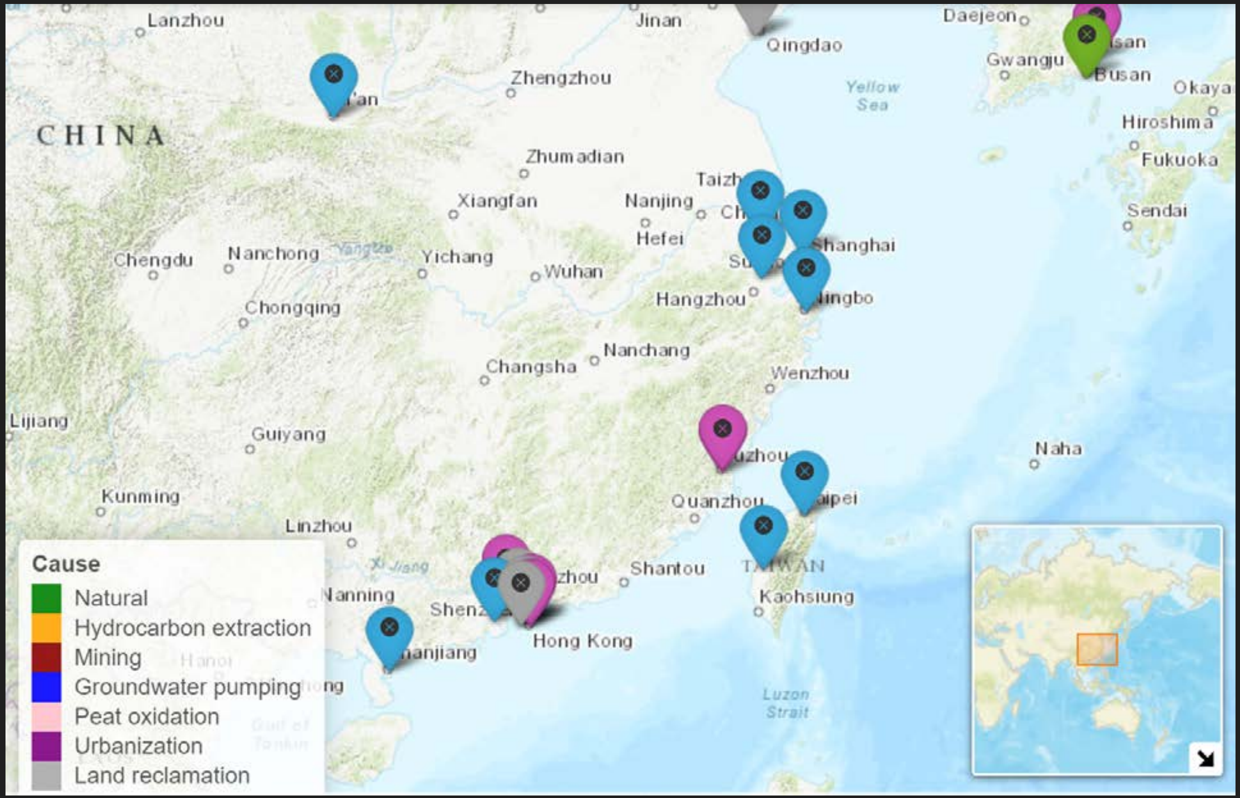
Virginia Tech, USA

December 4th 2020

Land subsidence is a serious problem in many regions of the world

UNESCO's Land Subsidence International Initiative has produced a world subsidence map that describes the nature and extent of hundreds of land subsidence areas around the world

https://www.landsubsidence-unesco.org/maps/



Land subsidence due to groundwater pumping is a serious problem in China and Taiwan

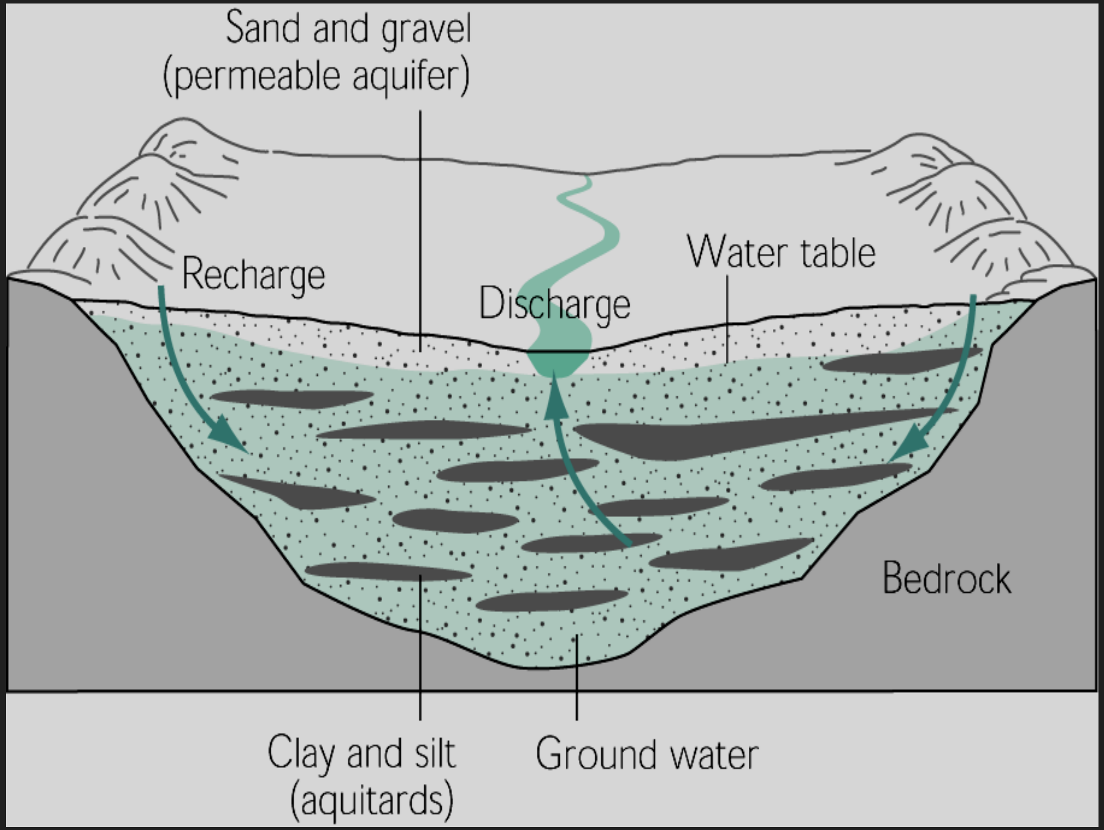
Much of west central Taiwan has experienced severe land subsidence due to pumping from agriculture and aquaculture

The effects of excessive groundwater pumping

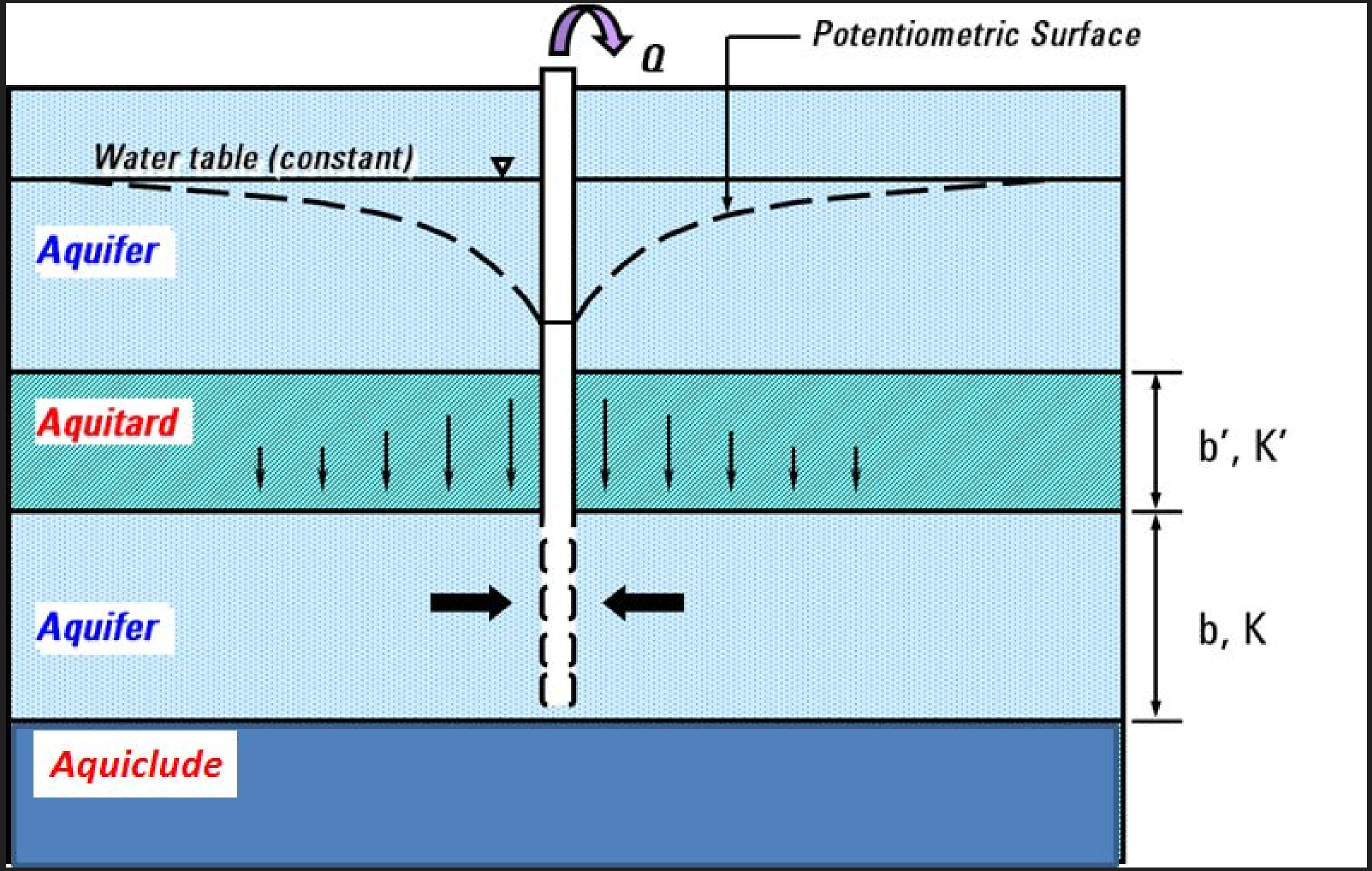
Drawdown of confined aquifers due to a reduction in pore pressures

A hydromechanical response occurs as the decrease in pore pressure causes an increase in effective stress within the porous framework

The increased effective stress results in compaction of the fine-grained deposits of the aquifer system, which manifests as subsidence of the land surface



Definition of a confined aquifer

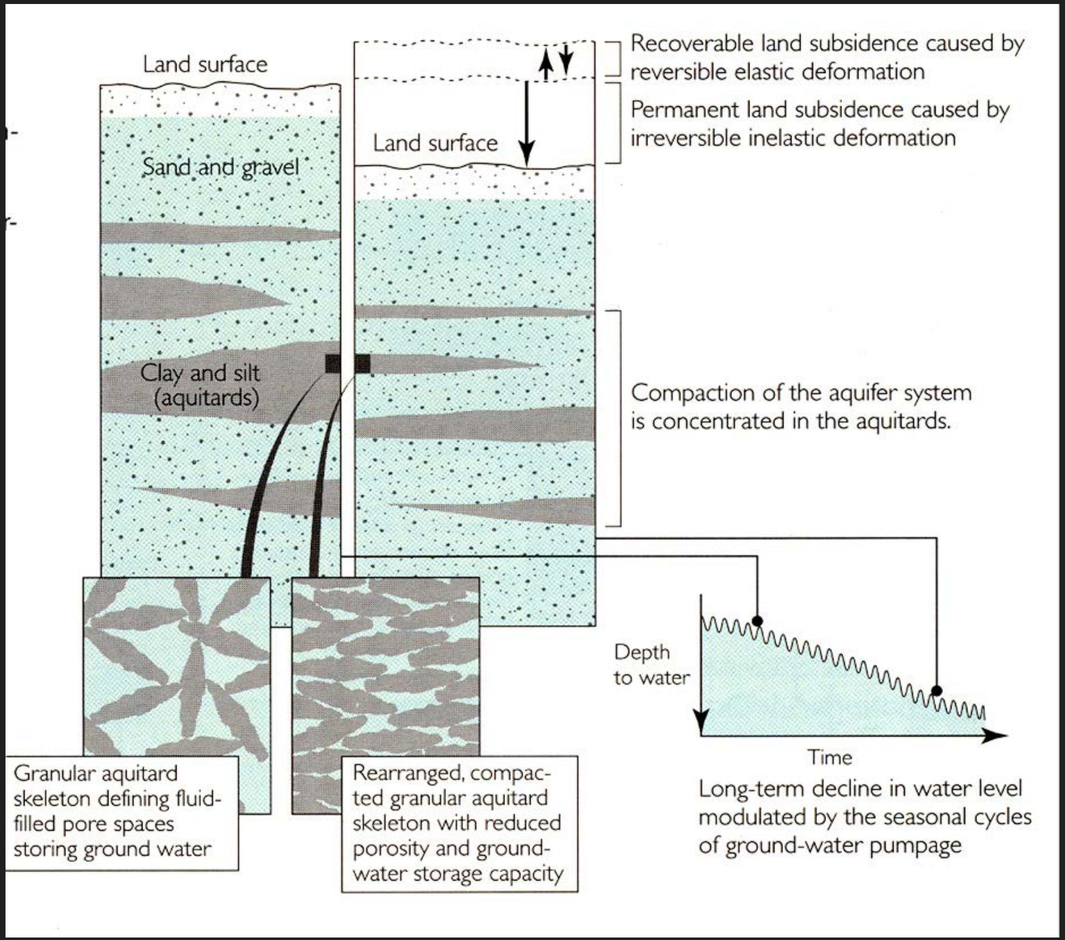


1. Aquifer is bounded above and below by a much lower permeability confining unit
2. Water level in well tapping the confined aquifer rises above the top of the aquifer of known thickness

A Theis type confined aquifer:

1. Infinite radial extent
2. Constant thickness
3. Perfectly confined
4. Horizontal flow

Vertical compaction is well known and its causes have been well established



From Galloway et al., 1999

Aquitard drainage model. Coarse-grained aquifers respond elastically while fine-grained interbeds respond inelastically.

Some important observations regarding aquifer deformation

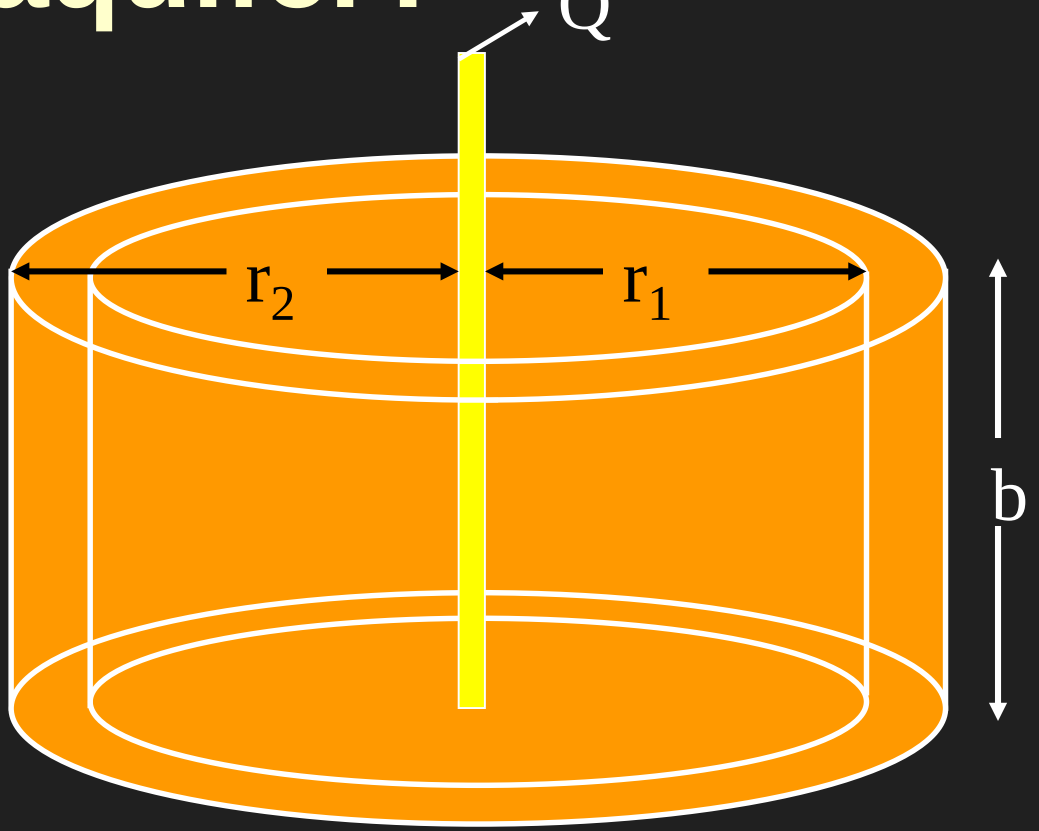
- Storage estimates are largely insensitive to changes in water level, while they are extremely sensitive to deformation changes.
- When measured, horizontal deformations have been shown to be of the same order of magnitude as the vertical deformations
- Pumping induced deformation has been observed to occur beyond the hydraulic radius of influence of the pumping well
- The aquitard drainage model does not address horizontal deformation

Horizontal aquifer deformation has been largely ignored because…

- It is mathematically expedient to ignore horizontal strain (Jacob, 1940)
- It makes many analytical solutions for calculating deformation intractable
- It is assumed to be unimportant
- Historically, there was no easy way to verify horizontal motions in the field

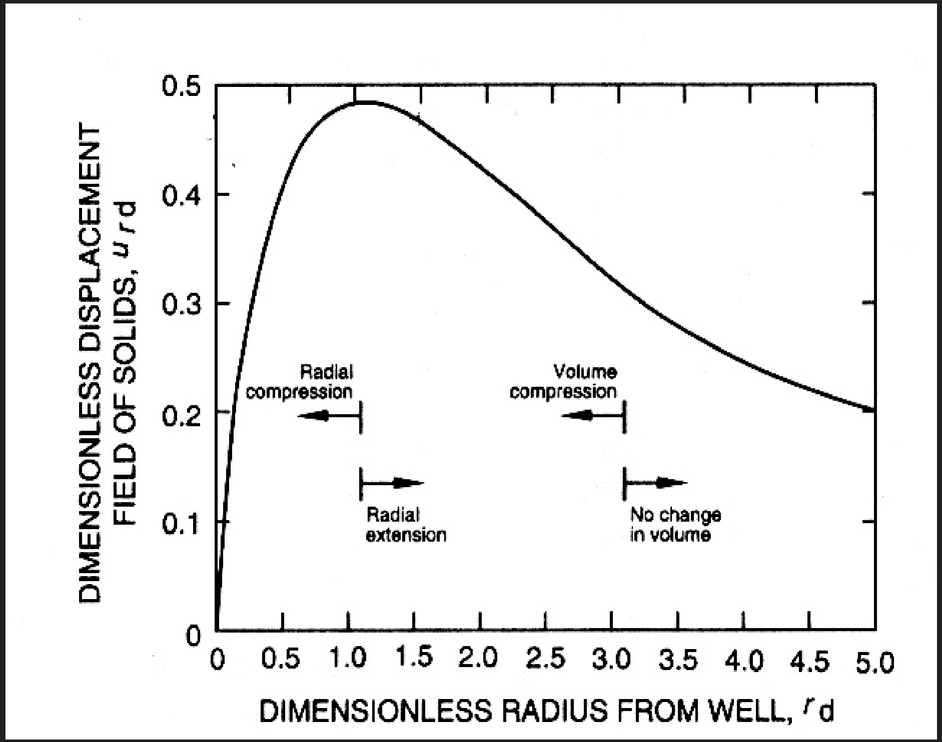
What happens when we pump a confined aquifer?

- Traditional hydraulics assumes that only fluid is in motion during pumping and that the granular matrix is fixed, or that only vertical compression occurs as water is removed from storage



$$\Delta V_w = Qt = \left(\varepsilon_v + \rho_w g n \beta (dh)\right)\ \pi\left(r_2^2 - r_1^2\right) b$$

What happens to the aquifer matrix when a pumping well is turned on?

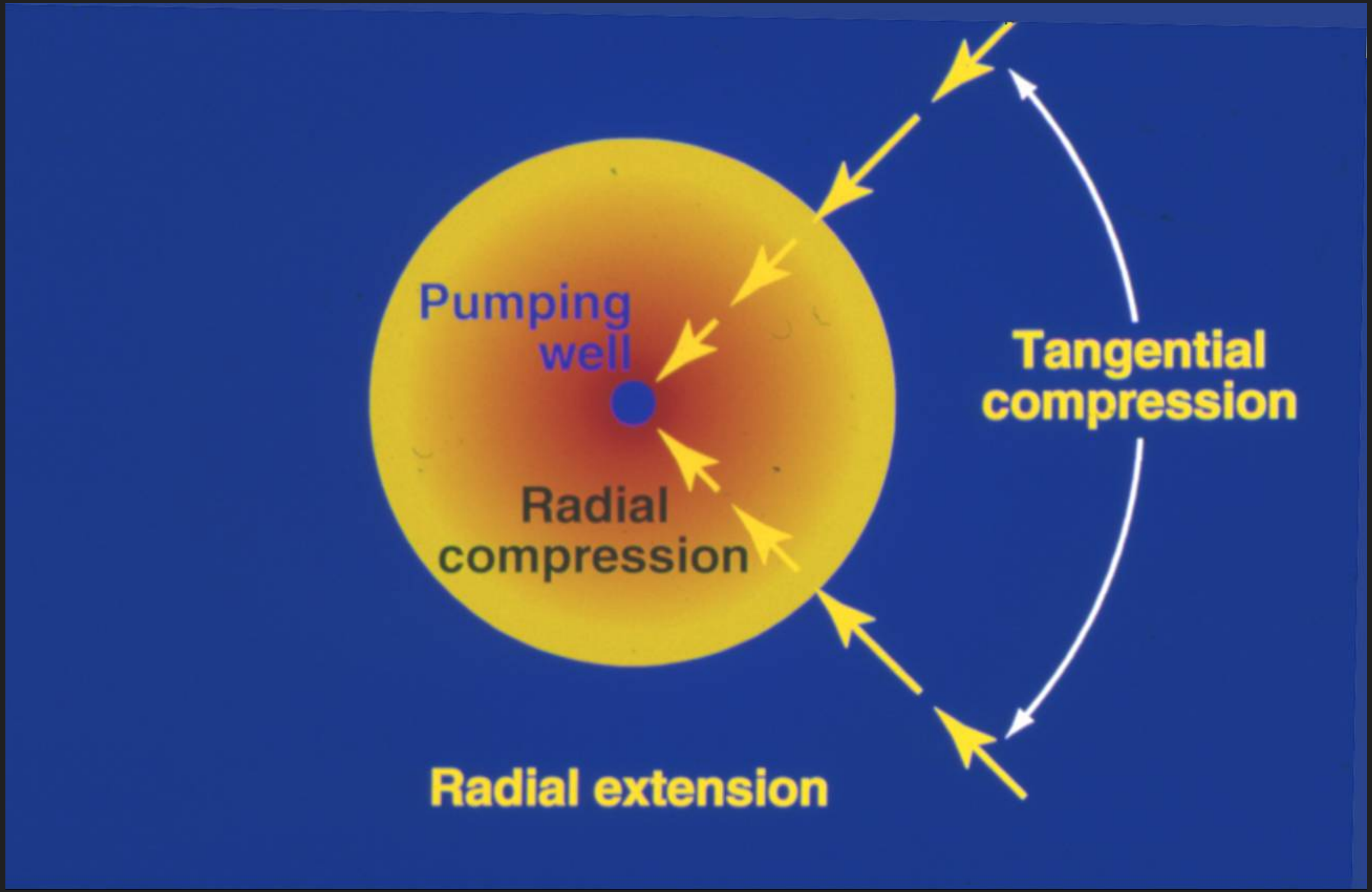


Granular velocity vs. time

Granular displacement vs. distance

from Helm (1994)

Strain distribution during pumping



In terms of volume strain this means:

$$\varepsilon_v = \varepsilon_{zz} = \frac{\Delta b}{b}$$

$$S = \frac{b\varepsilon_v}{dh} + \rho_w g b n \beta$$

MODFLOW along with the SUB (or IBS) package is used to simulate vertical deformation for the condition of zero horizontal strain

Volume Strain for the more general case of three-dimensional flow and deformation

- A Biot model is used to simulate strain components in cylindrical coordinates

$$\varepsilon_v = \varepsilon_{rr} + \varepsilon_{\theta\theta} + \varepsilon_{zz}$$

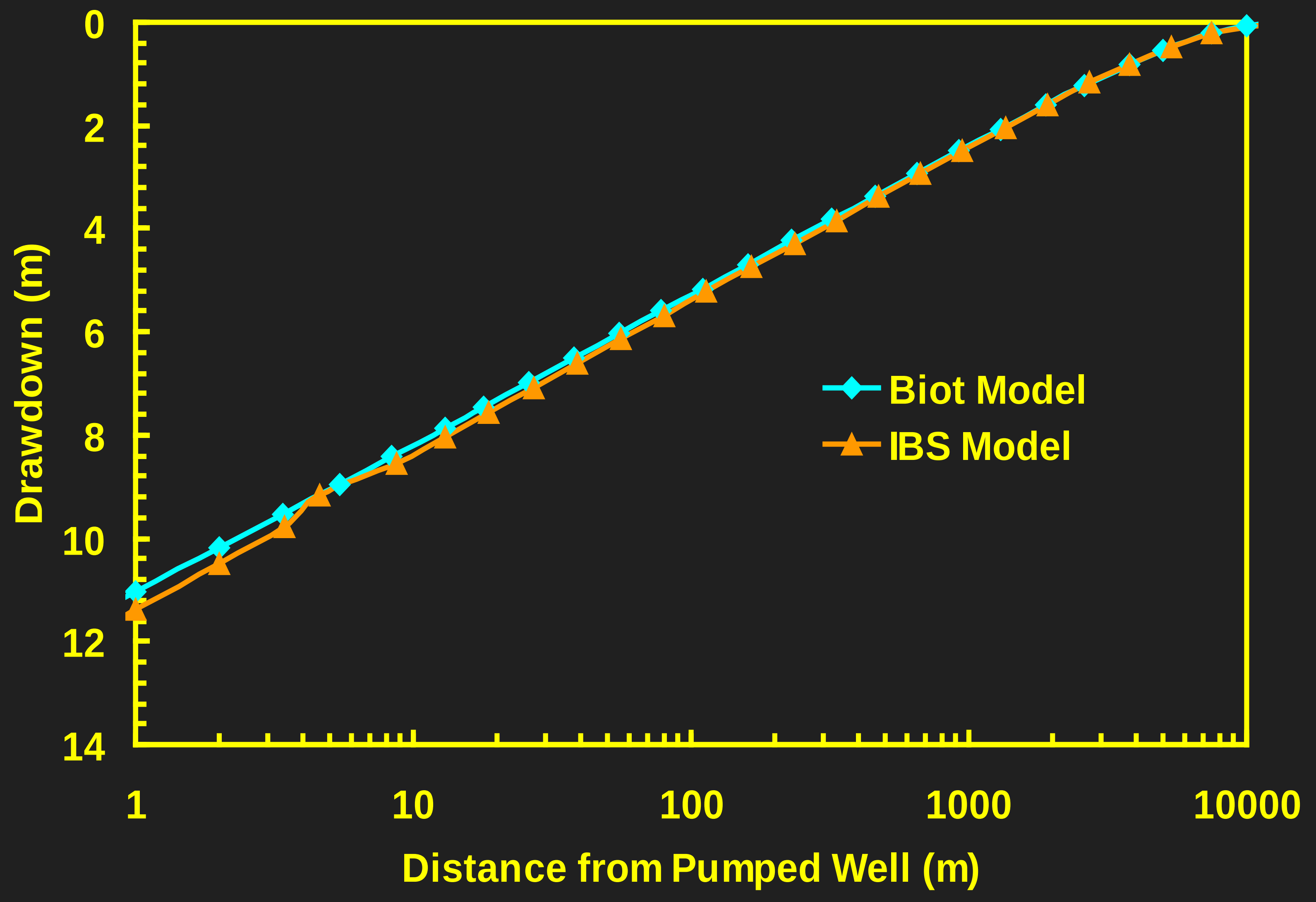
- Which is also related to the displacement field

$$\varepsilon_v = \nabla \bullet \mathbf{u} = \frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z}$$

Why should we care about horizontal strain and deformation?

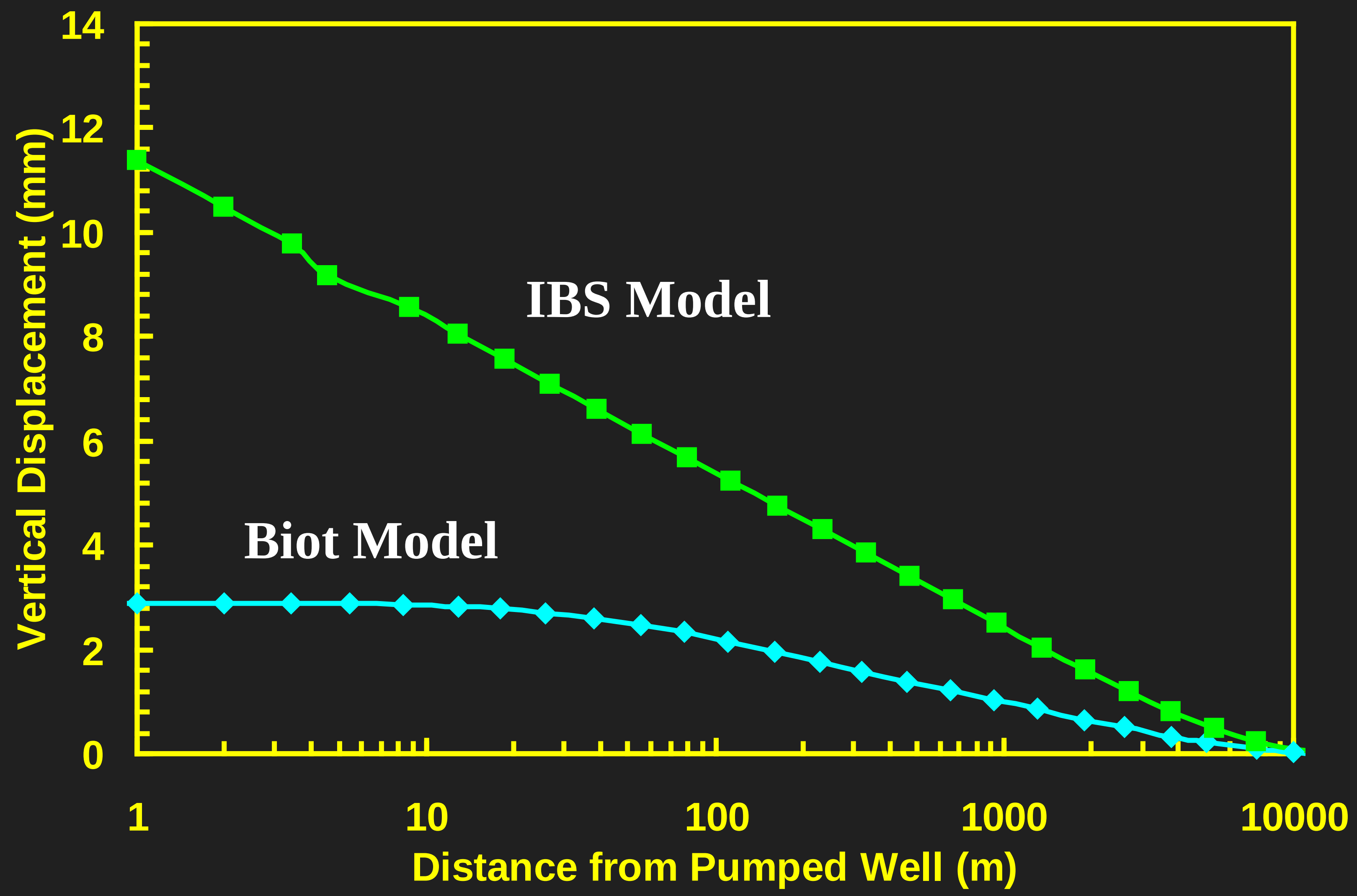
1. Including them allows us to more accurately identify the source of pumped water and aquifer behavior beyond the cone of depression (radius of influence).
2. Results in more accurate estimates of storage

Drawdown after 20 days of Pumping

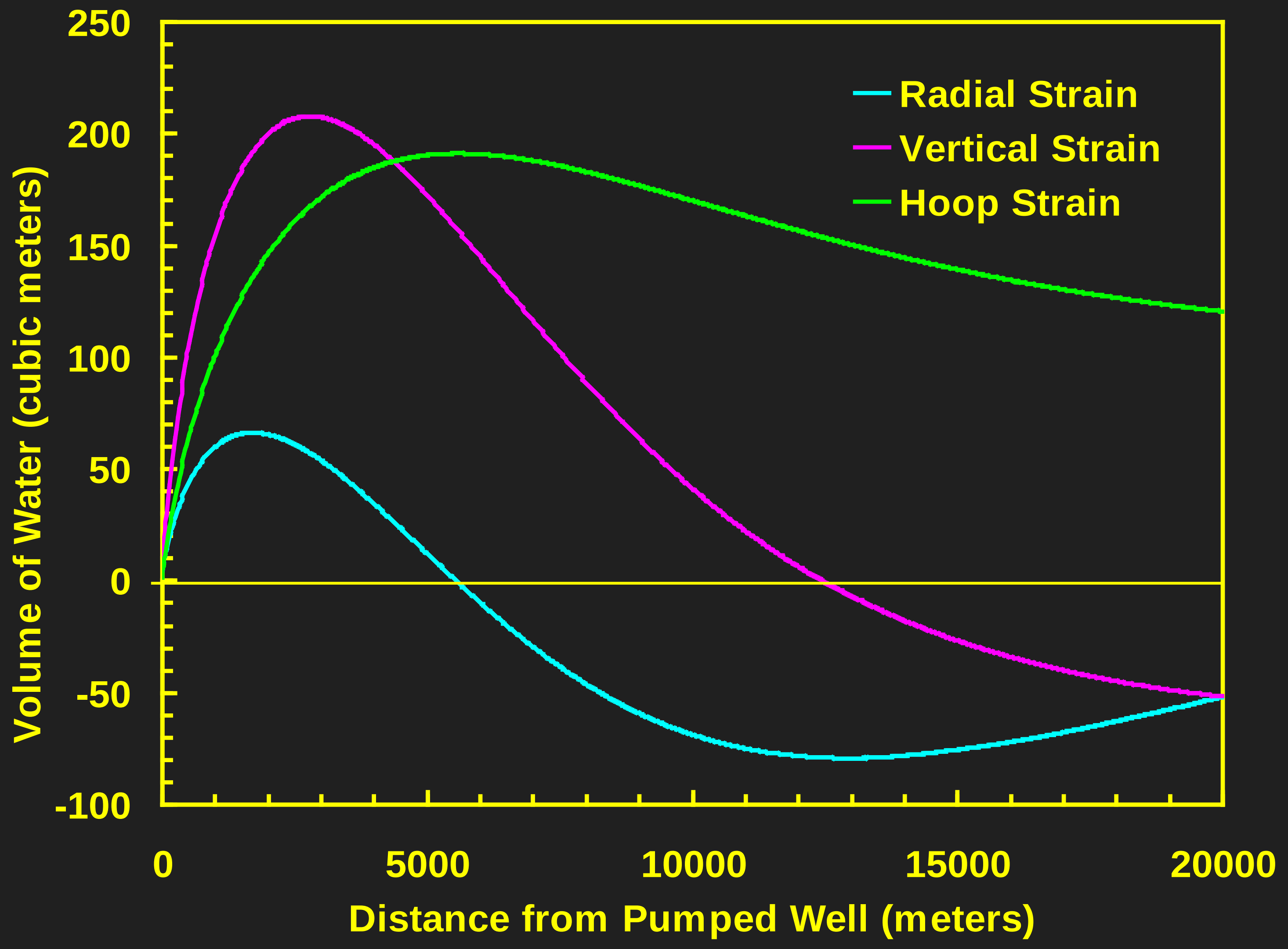


Theis aquifer system

Vertical compaction after 20 days of pumping



Strain Components after 20 days of Pumping



Theis Confined Aquifer

Pumping Time	Percentage of Total Volume Pumped from Horizontal Strain
3 Hours	55
1 Day	56
20 Days	64
1 Year	70

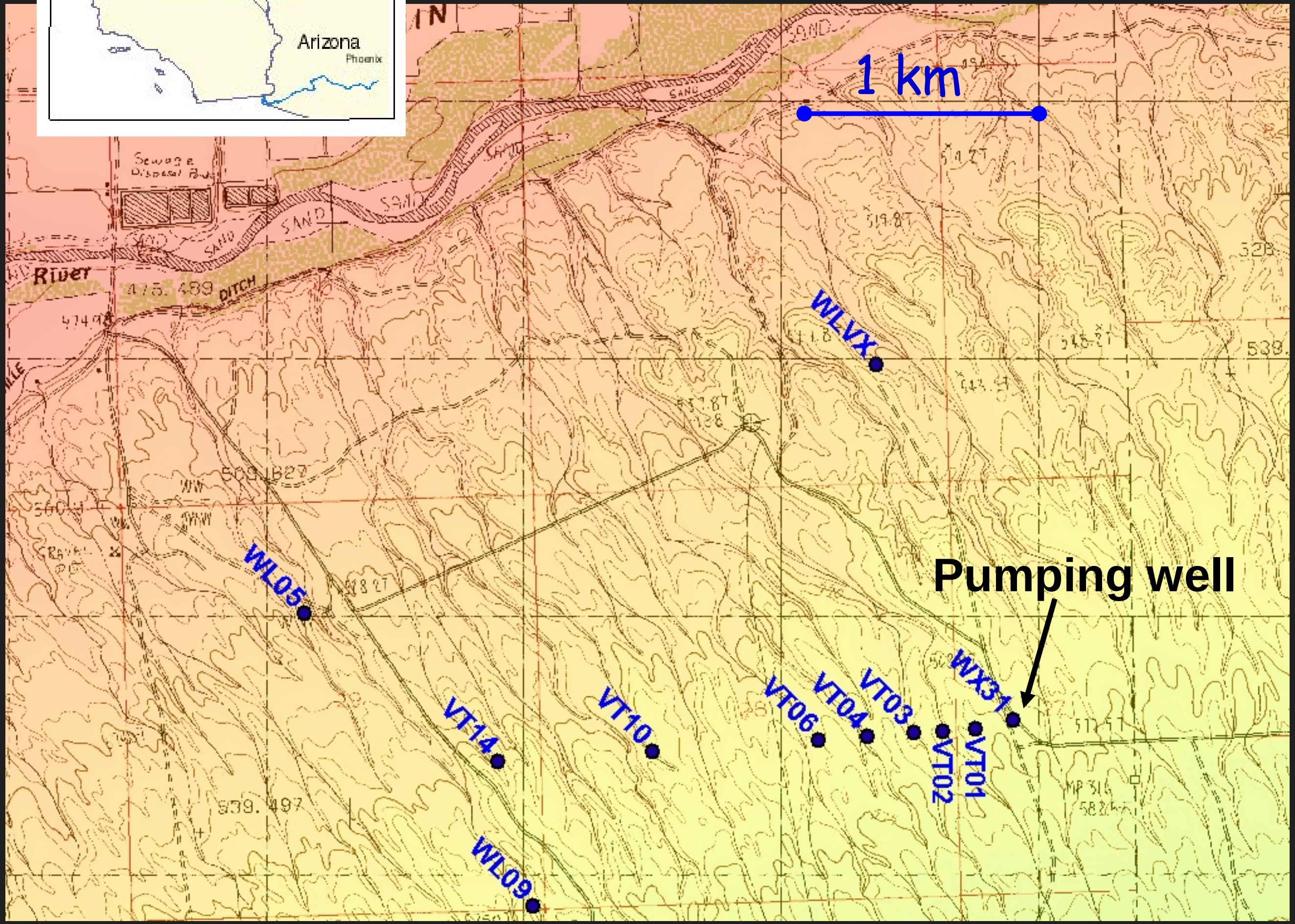
Why we should care about horizontal strain and deformation?

3. Because deformations can be used to characterize the aquifer even in the absence of water-level data
4. It can be used to identify the presence and poromechanical attributes of nearby faults.

WX31

Mesquite, NV

Study area



1 km

Area occurs in alluvial deposits consisting of silts, sands, and clays of lacustrine and meandering-stream origin. 80m of brittle unsaturated zone overlies aquifer

GPS receivers and antennas were installed at different radii from the pumping well

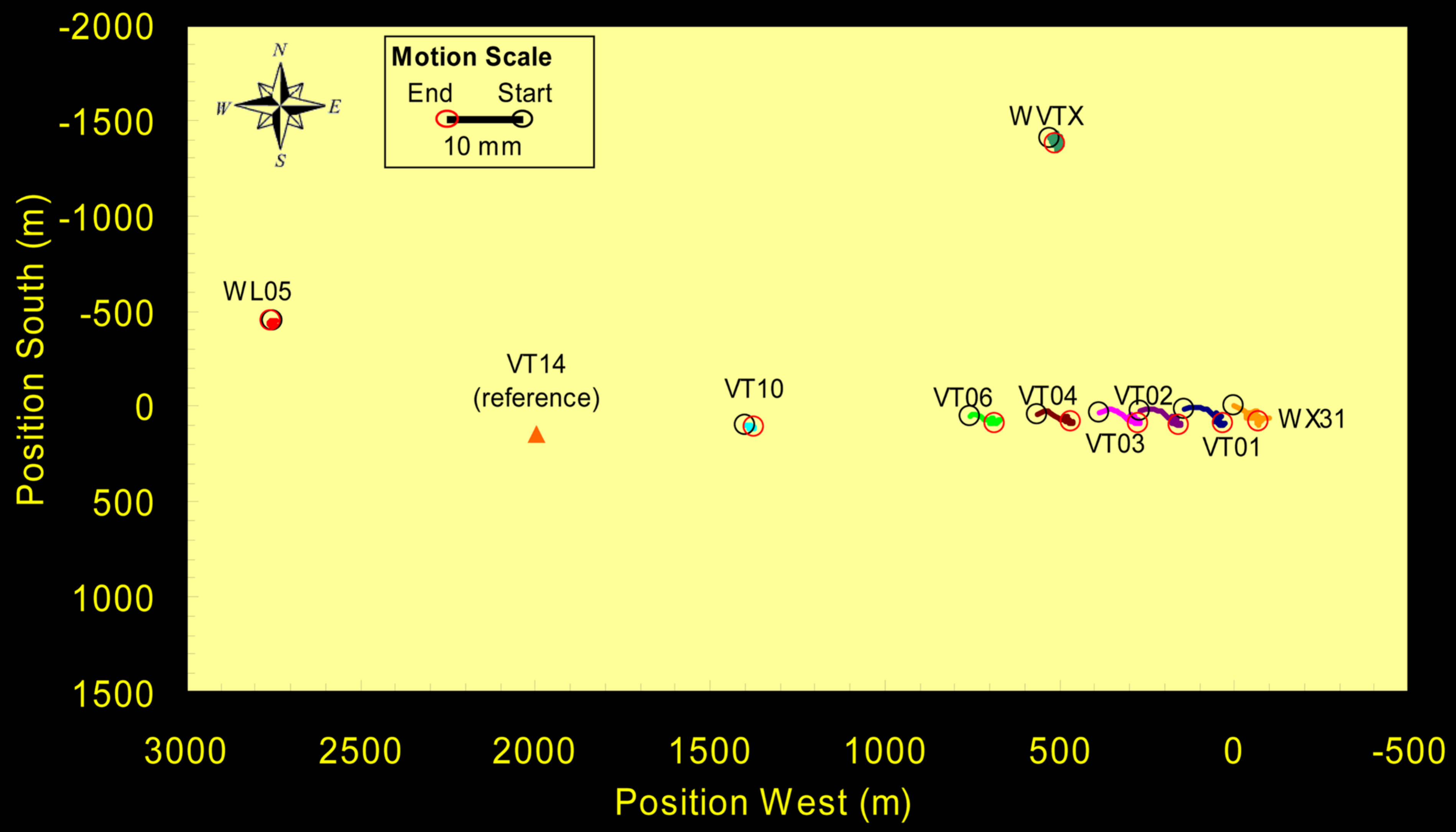
Data were collected at 20 sec intervals over about 1 month of time

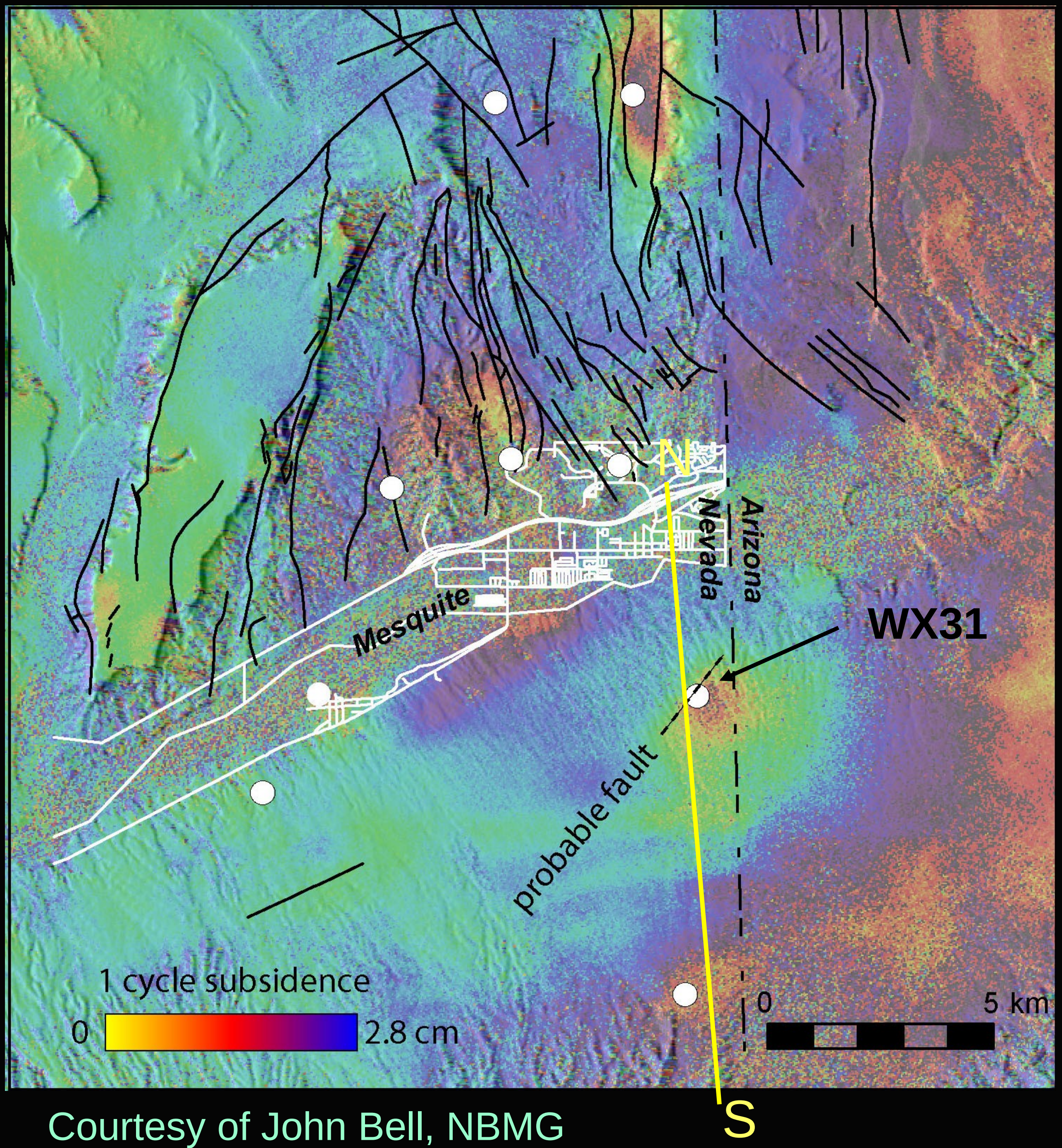
A municipal well was installed on the alluvial fan above the Virgin River where no prior pumping had occurred

Municipal well pumped cyclically at nearly 12 m^3/min

Mesquite is a booming retirement area

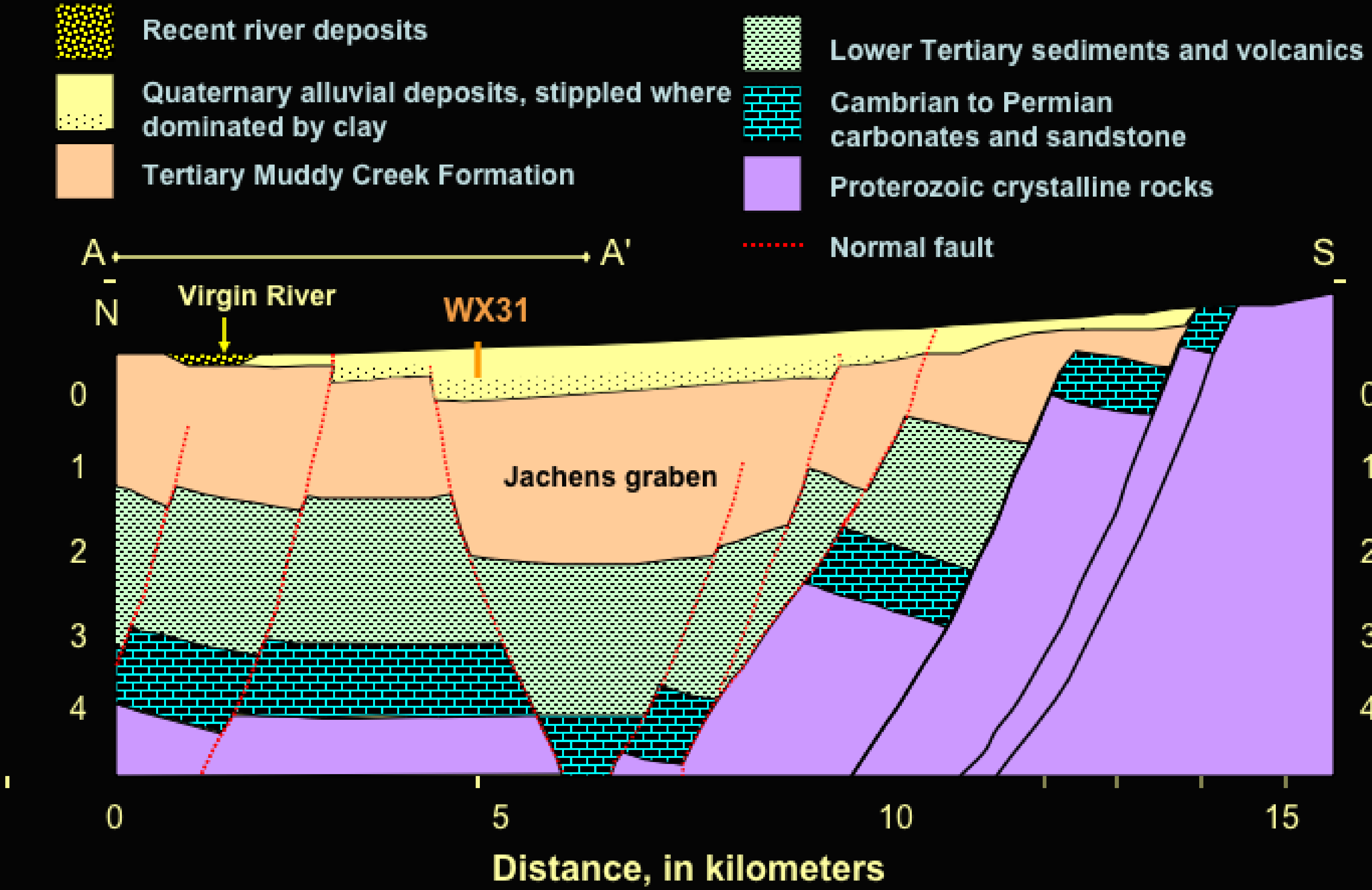
Displacement of Stations over first 22 Days of Pumping





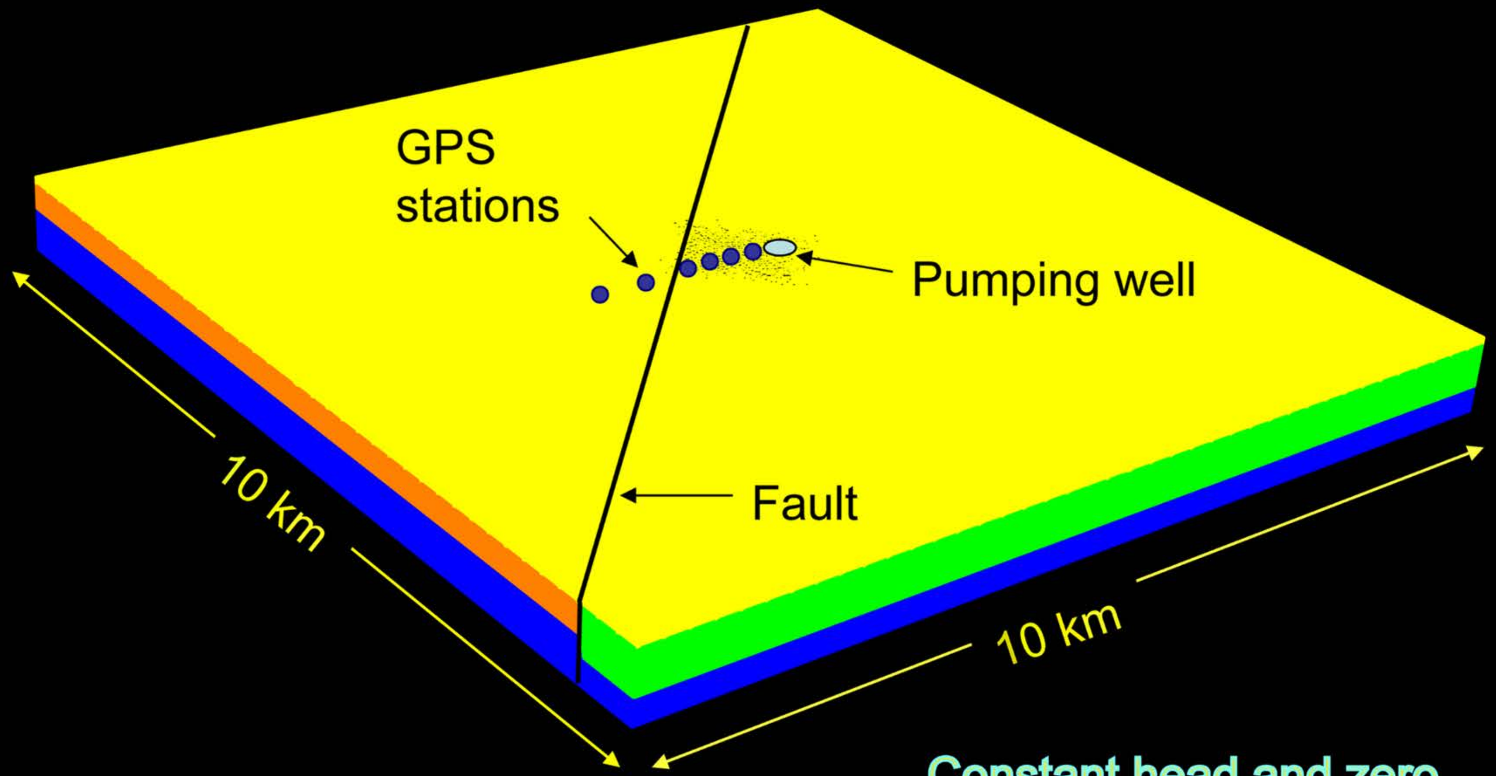
Courtesy of John Bell, NBMG

InSAR data, that includes the period of the aquifer test, shows a subsidence bowl offset to the southeast



Modified from Dixon and Katzer, 2002

Mesquite conceptual model

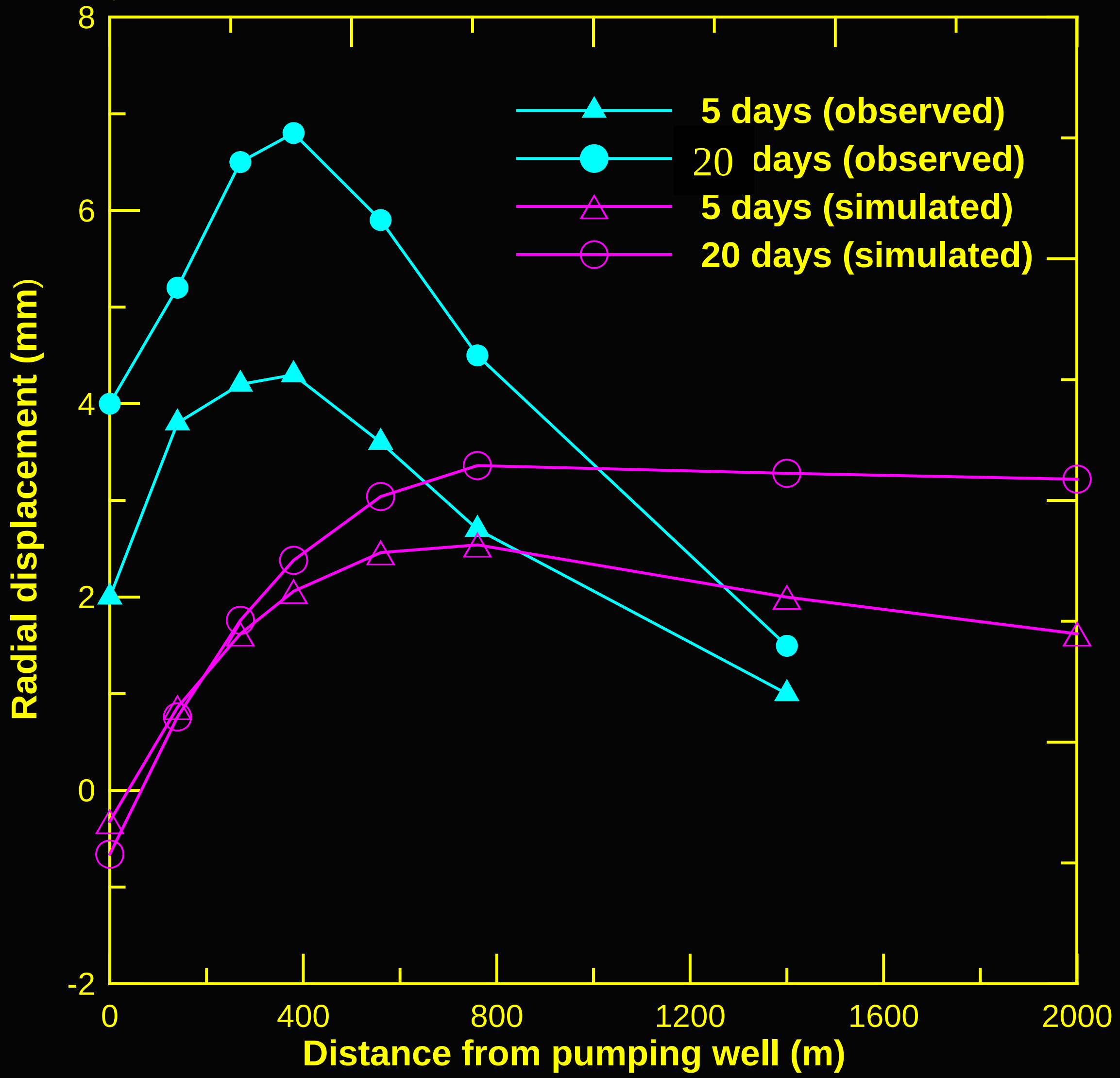


- Unsaturated zone (85 m)
- Principle aquifer (400 m)
- Secondary aquifer (200 m)
- Clay (400-600 m)

Constant head and zero displacement boundaries along all four sides

ABAQUS was used for deformation modeling

Calibration consisted of comparing simulated and observed east-west, vertical and north-south displacements at GPS stations

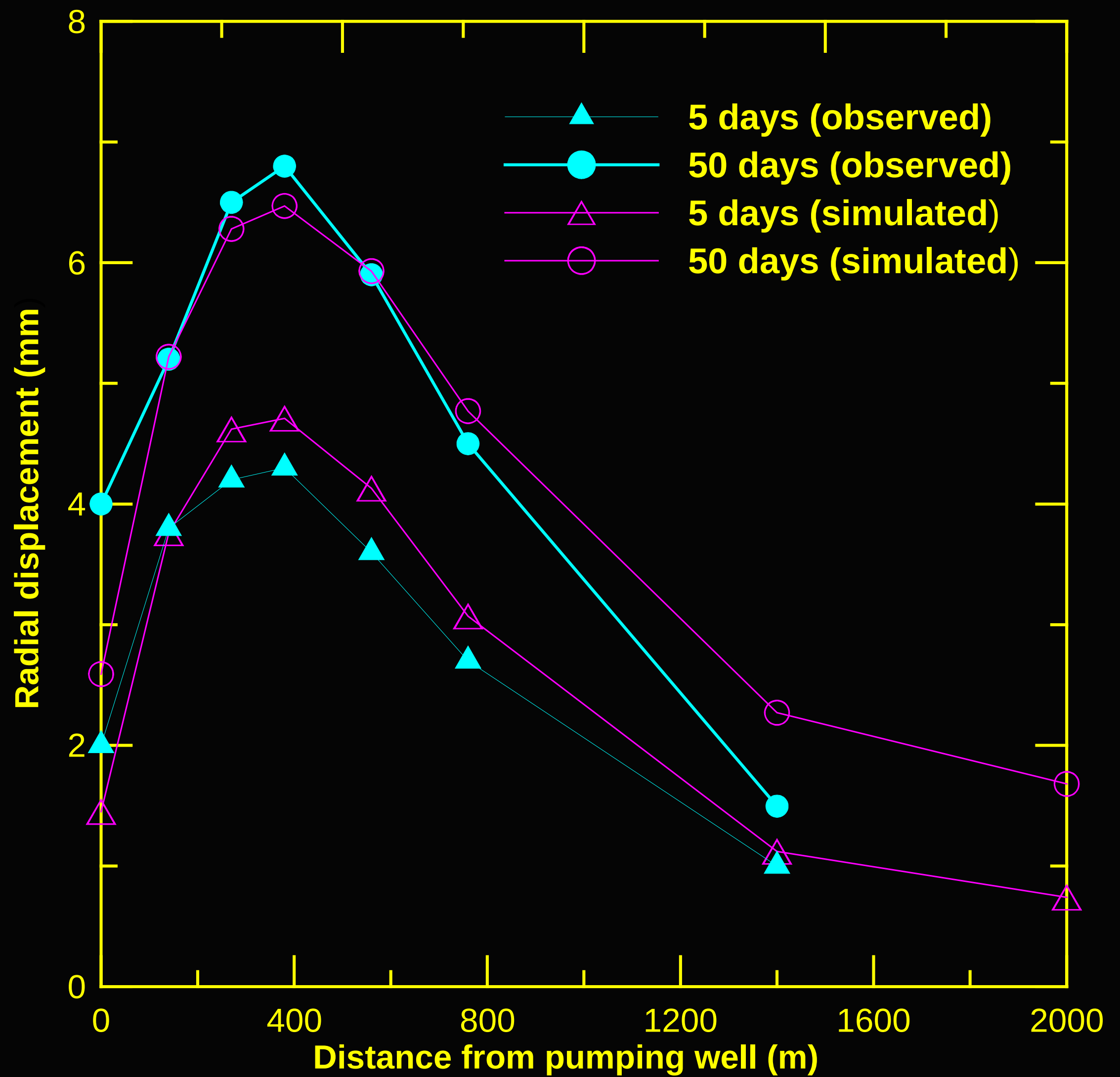


Plot shows results where fault is simulated as a simple heterogeneity change

During the calibration process it was discovered that…

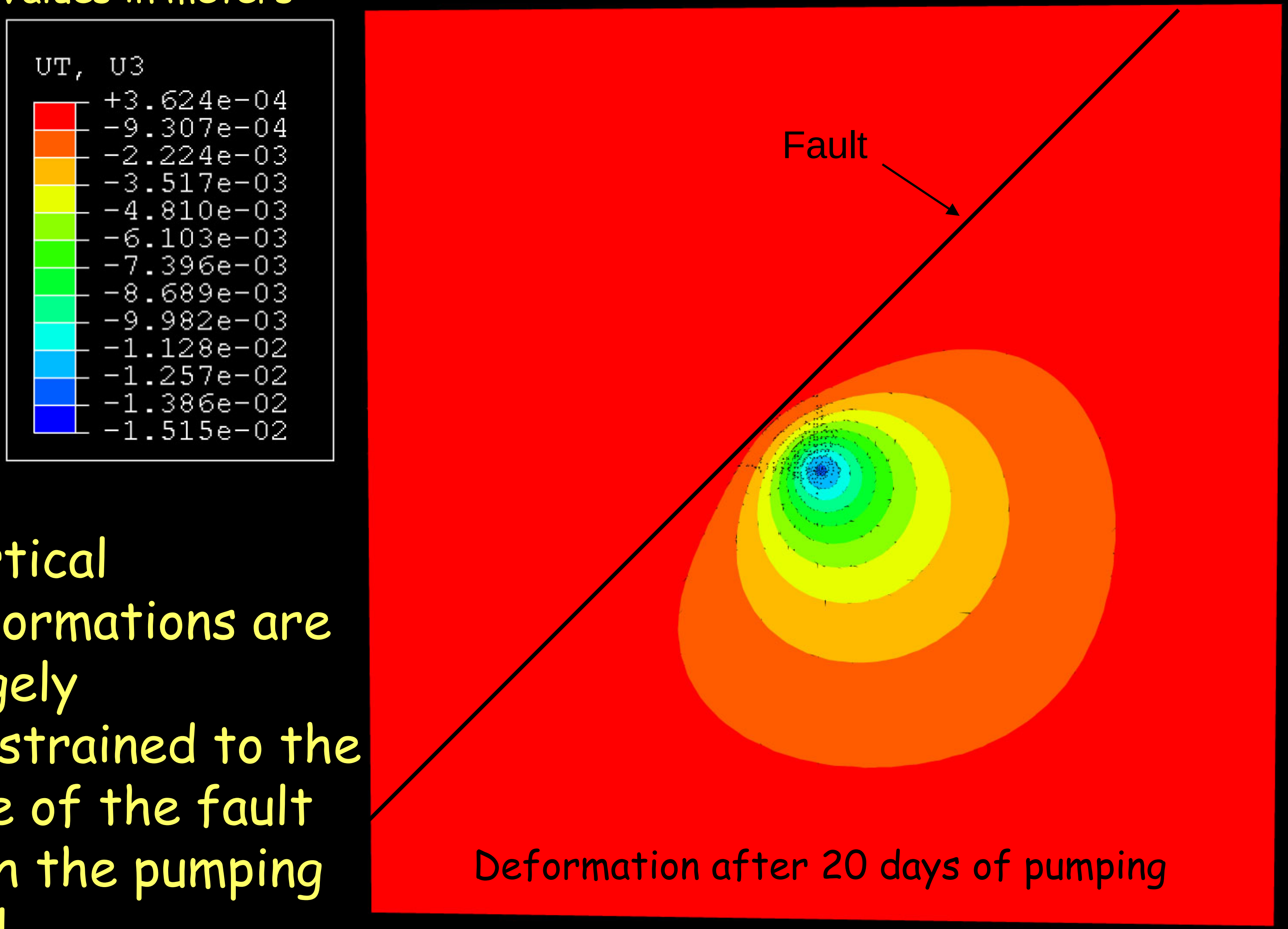
- Low permeability fault induces WX31 to move toward the fault and results in no horizontal deformation at GPS sites farthest from well.
- N-S fault orientation results in no north-south motion
- Fault appears to represent a semi-discontinuous mechanical boundary for vertical and horizontal deformation.
- Low storage fault does not impede radial migration to the west

The best match of observed vs simulated radial displacements occurs when fault is simulated as a zone of strain absorption (semi-discontinuous BC)



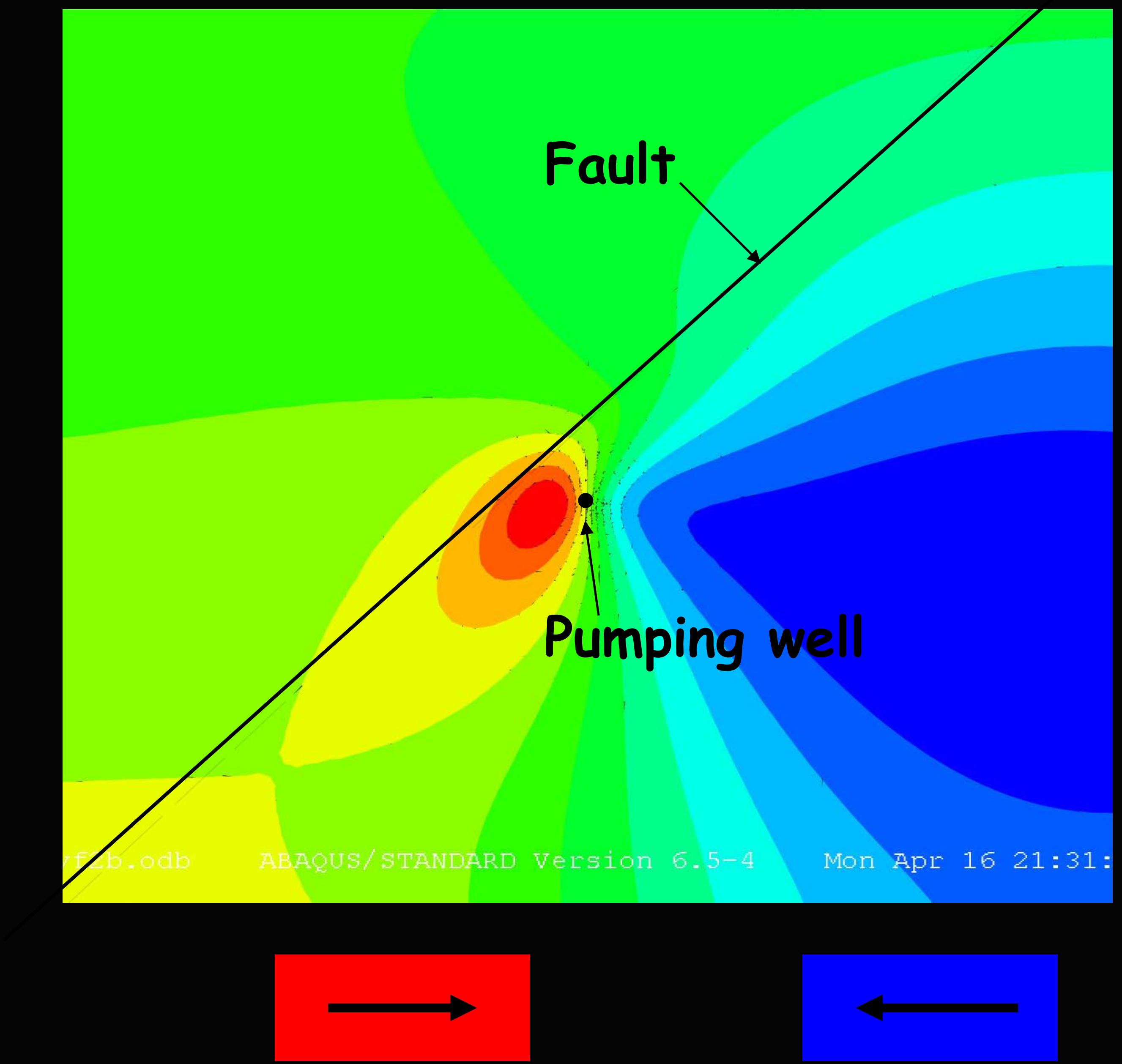
The fault is characterized as a semi-discontinuous boundary that acts to absorb areal strain, impeding it from being translated across the fault.

Values in meters



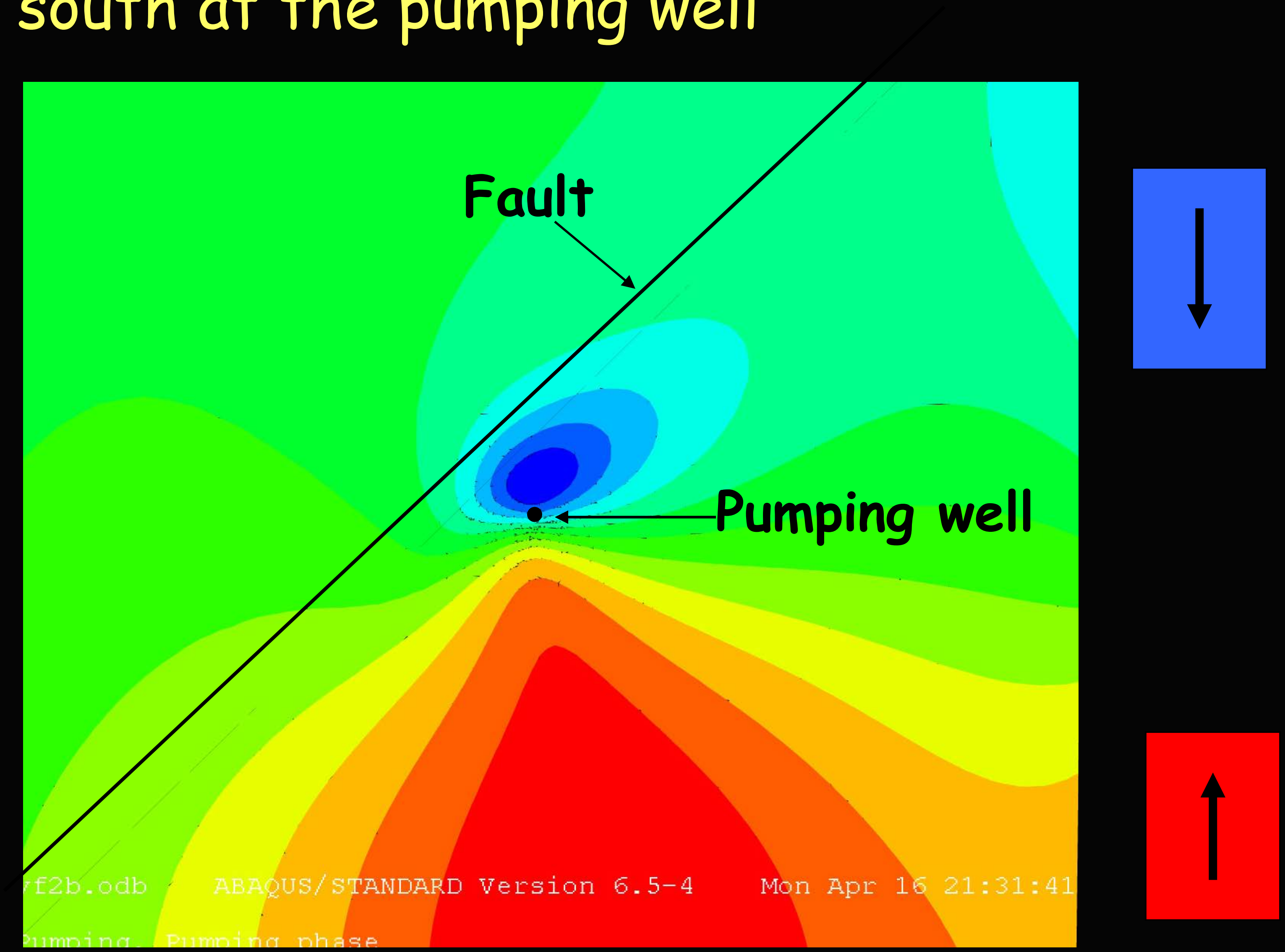
Vertical deformations are largely constrained to the side of the fault with the pumping well.

Simulated radial (east-west) displacements

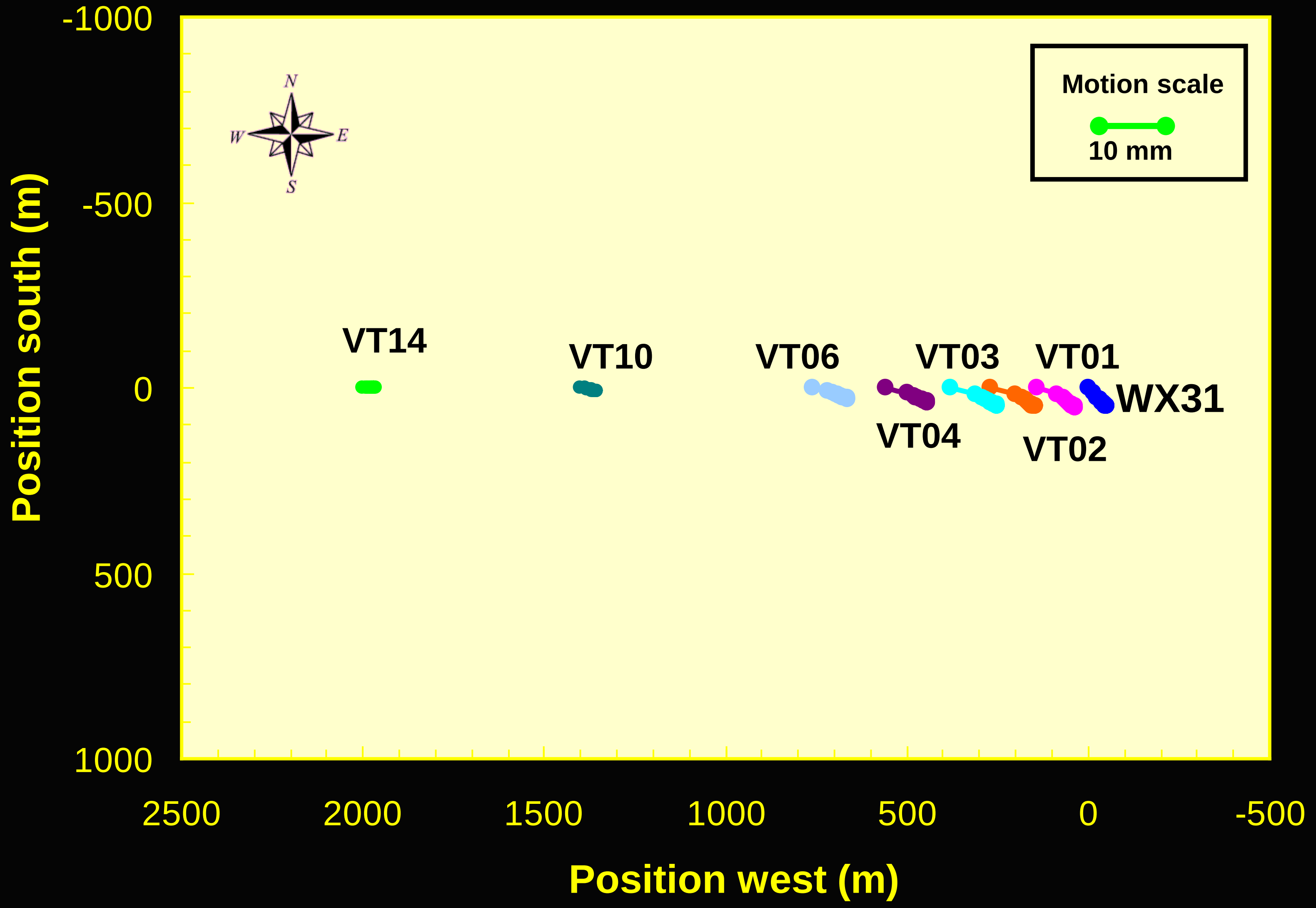


Results indicate fault induced radial motion at the pumping well away from the fault (to the east)

The fault induces tangential motion toward the south at the pumping well



Simulated displacements after 20 days of pumping



Why should we care about horizontal strain and deformation?

5. Because they are necessary to understand the mechanics of fissure formation and propagation
6. Because they are necessary to understand observed subsidence patterns adjacent to faults

The effects of pumping: subsidence and earth fissures

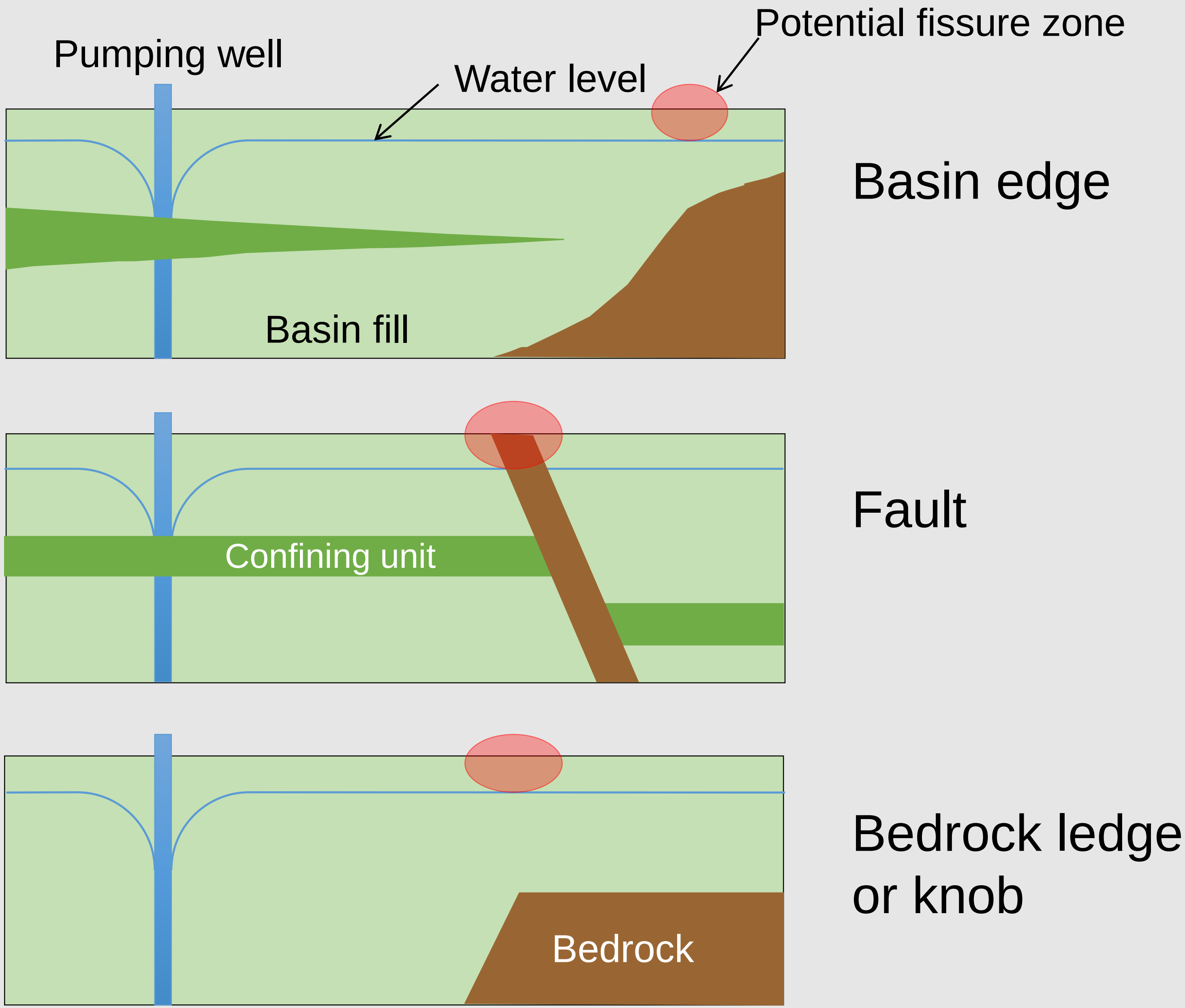
Important concept:
Earth fissures have been attributed solely to differential vertical displacement, but the genesis and location of fissures may be influenced more by horizontal deformation and strain.

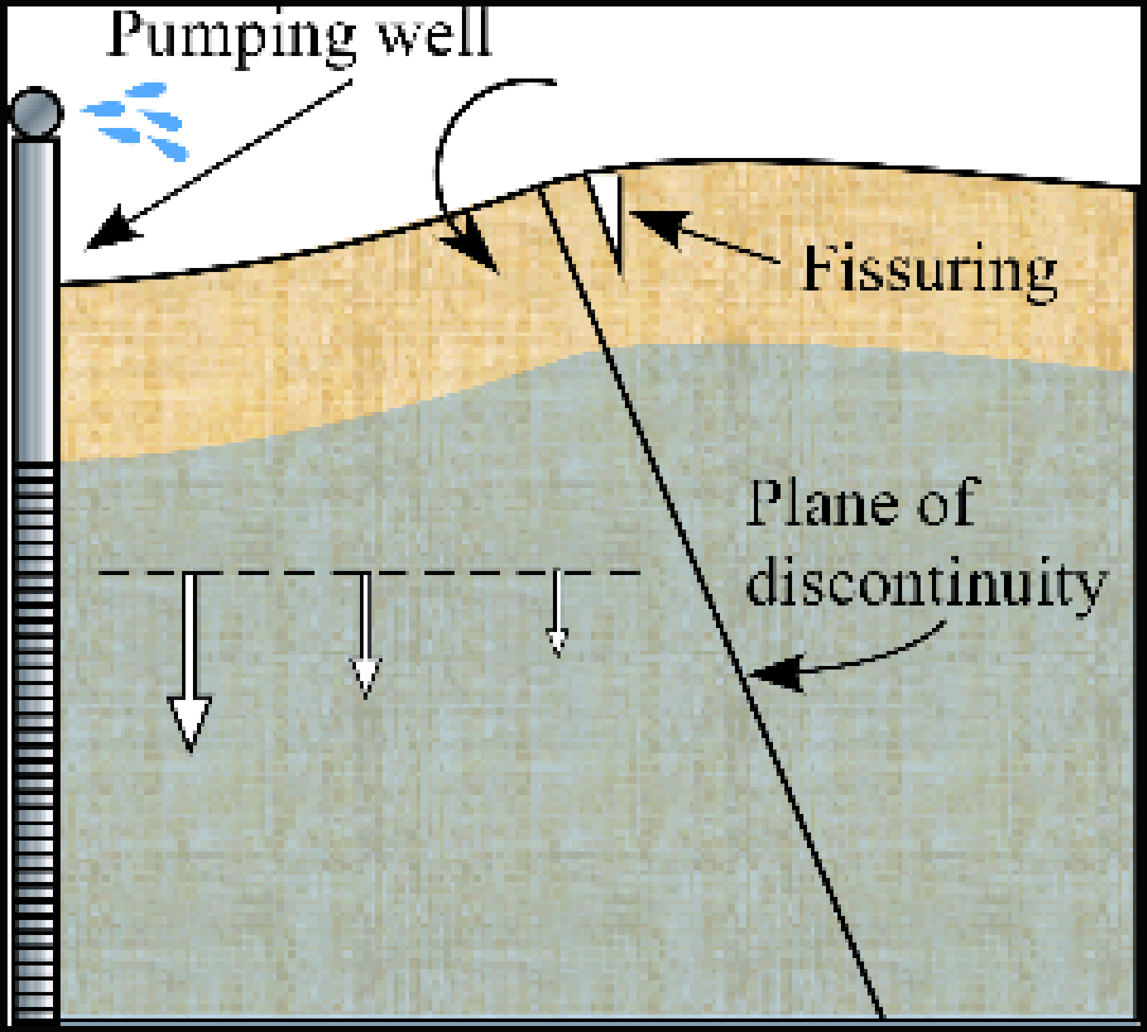
Earth fissures occur primarily because of heterogeneities in the pumped aquifer

- Abrupt changes in physical conditions can cause stress and strain to accumulate at the location of the change in properties
- These accumulations (or partitioning) of stress and strain are highly dependent on horizontal aquifer motions
- These accumulations (partitioning) are common at transformational boundaries

Earth Fissure in Pahrump, NV

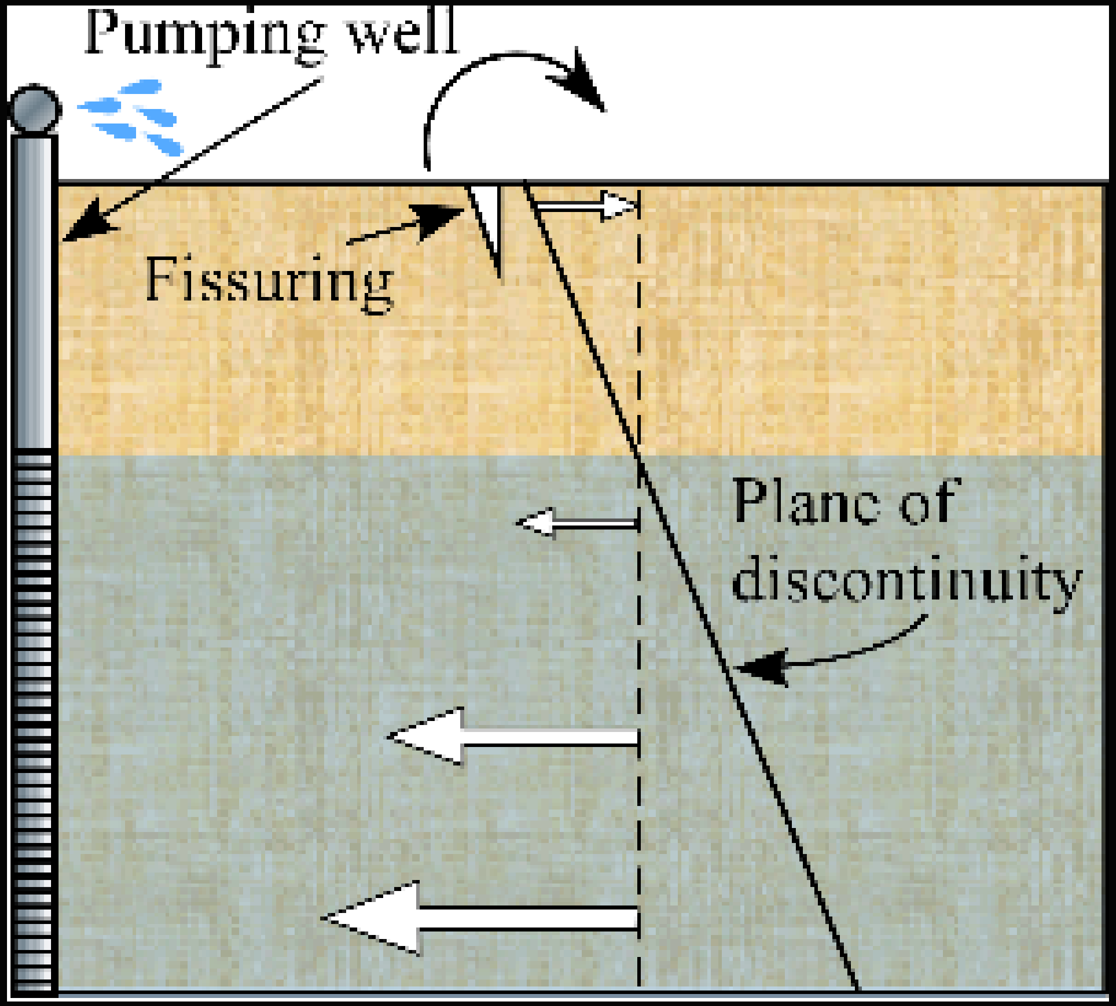
Transformational Boundary Types





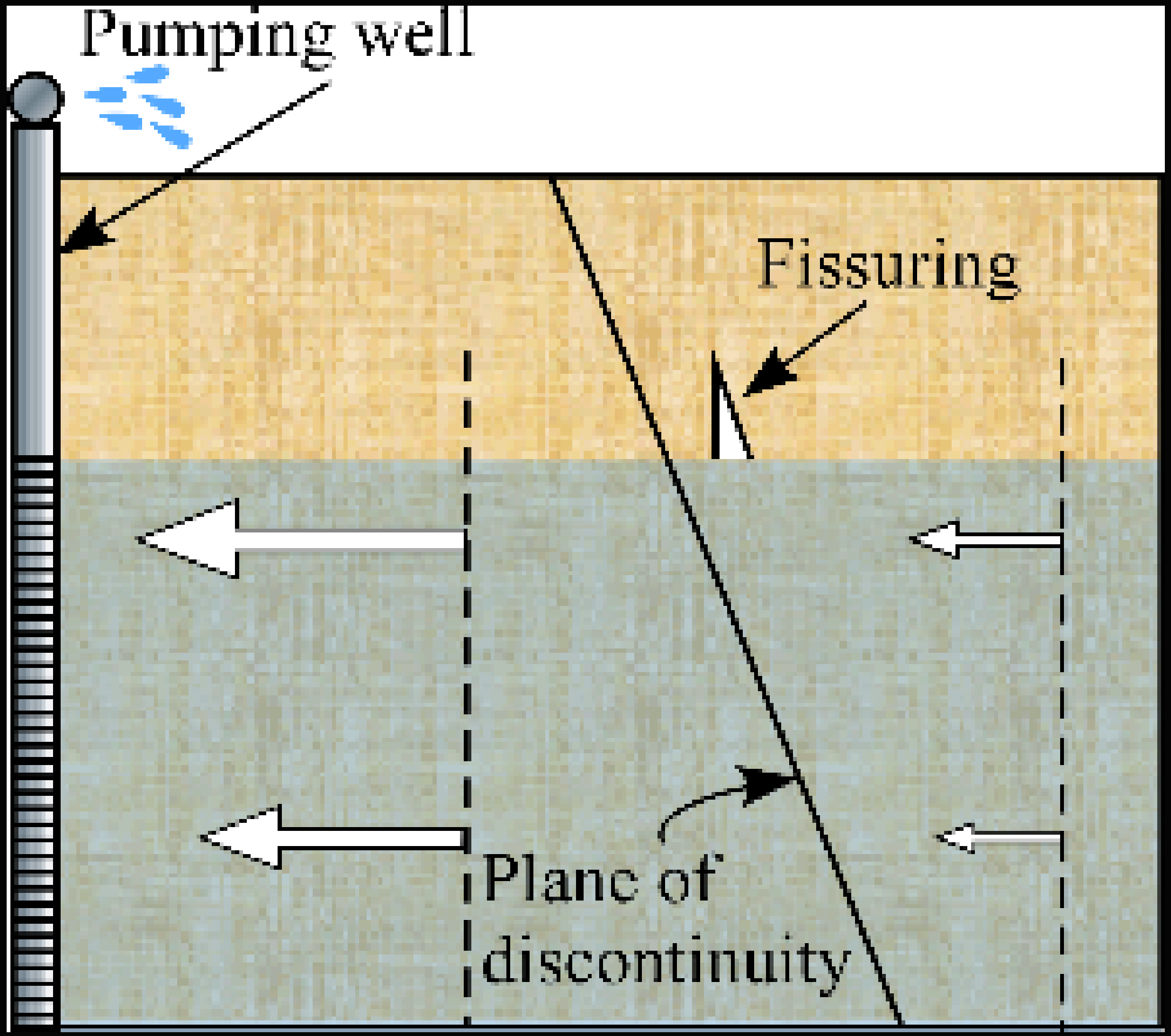
Under vertical strain conditions, the large vertical subsidence would tend to cause the fault to rotate in the direction of greatest subsidence.

This would result in fissures on the opposite side of the fault from the pumped well, but fissures would be observed to migrate downward from the land surface



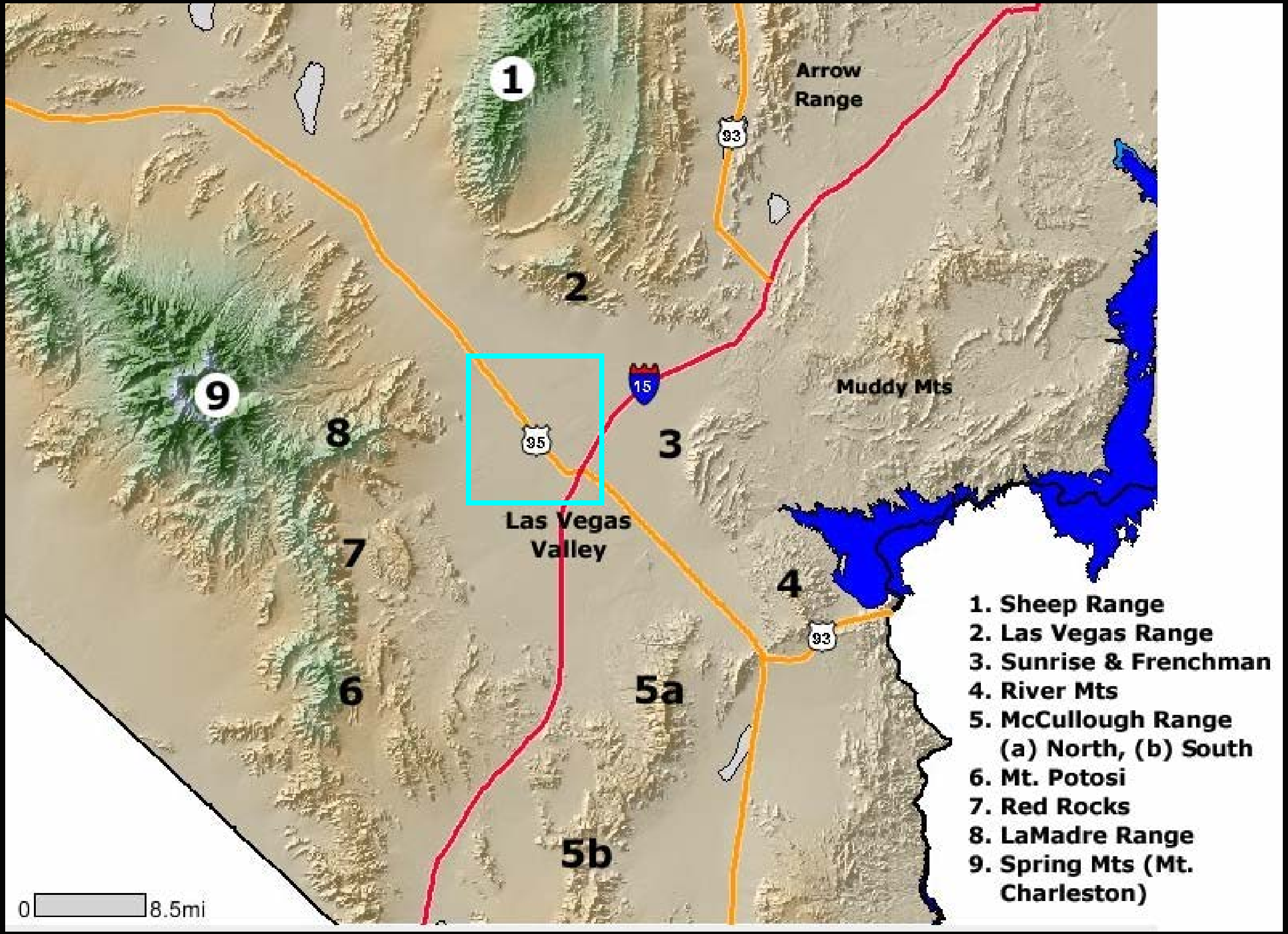
Under horizontal strain in which both the aquifer and overlying unit act as a single continuum, the fault would tend to rotate clockwise, resulting in fissures opening on the side of the fault with the pumping well.

These fissures would also tend to migrate downward from land surface.



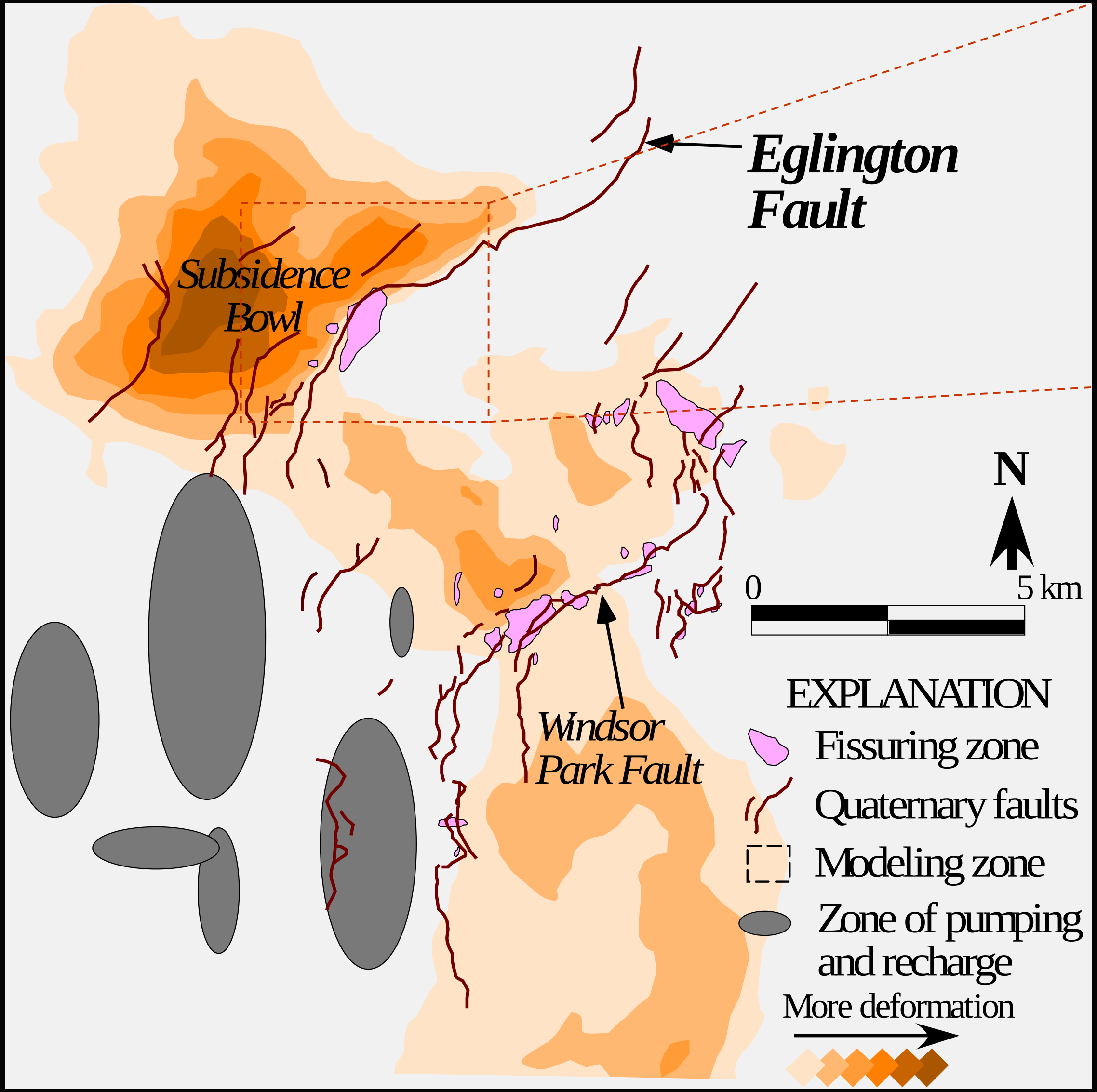
Under horizontal strain conditions in which the fault behaves as a mechanical discontinuity, The side of the fault nearest the well pulls away from the opposite wall. Fissures would tend to migrate upward from depth in the unsaturated zone.

Basin-Fill Faults



Las Vegas Valley represents a structural basin filled with up to 2400 m of Tertiary and Quaternary sediments

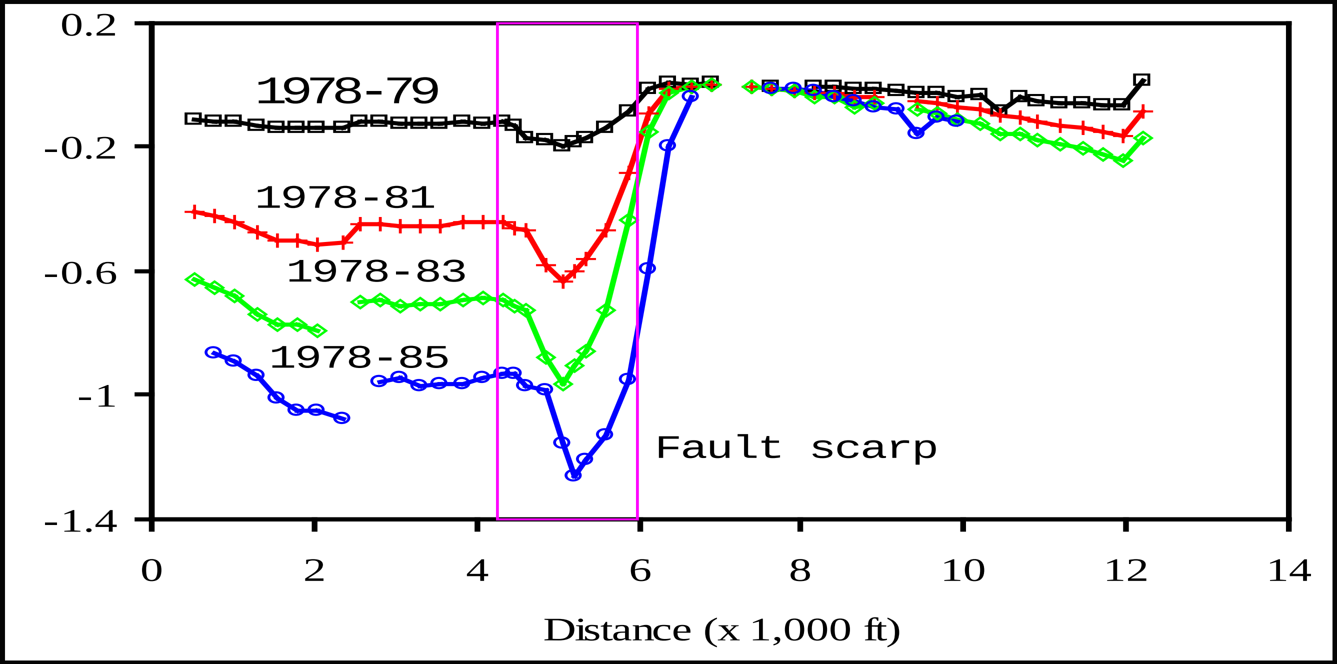
Basin-fill faults are prevalent throughout the basin
Earth fissures tend to occur near or adjacent to basin-fill faults



Northwest portion of Las Vegas Valley

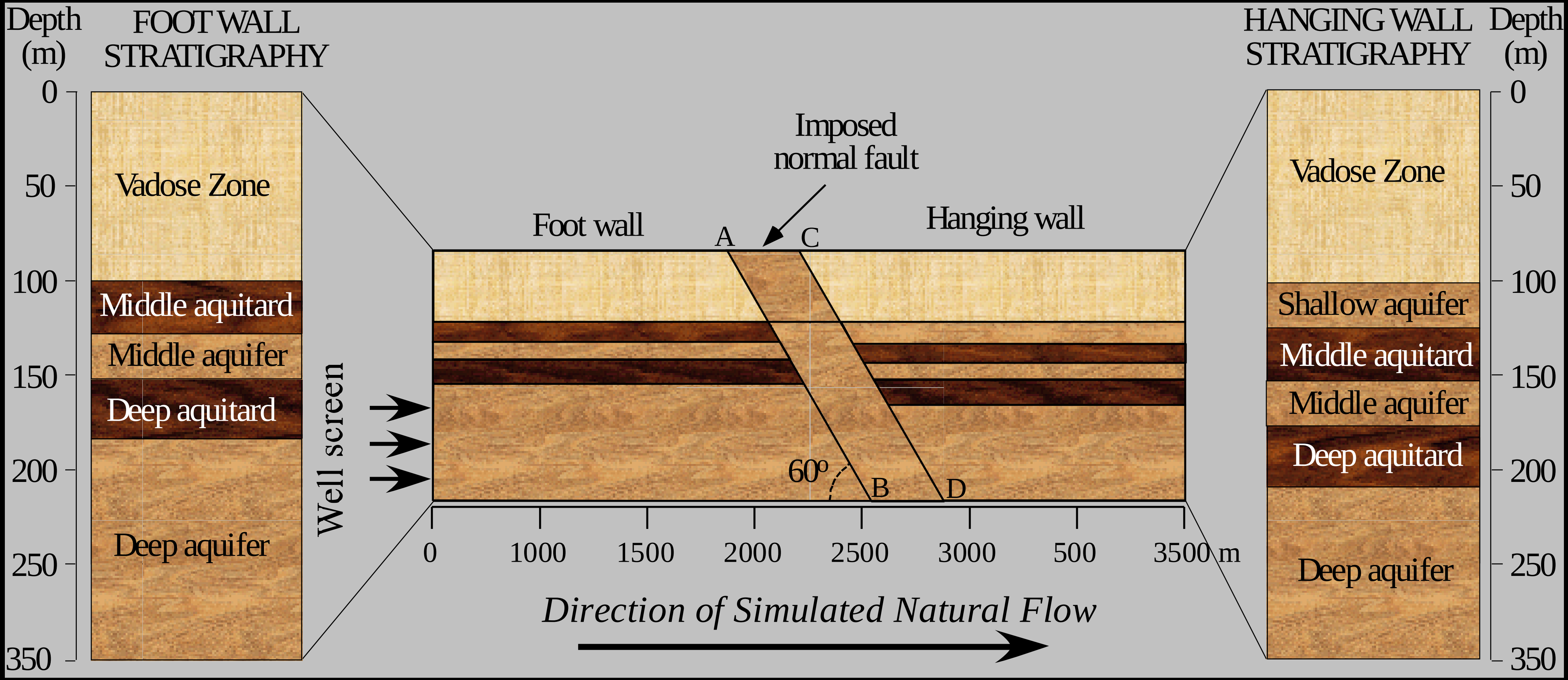
Hernandez-Marin (2009)

Measured subsidence (in feet) over a 7-year period



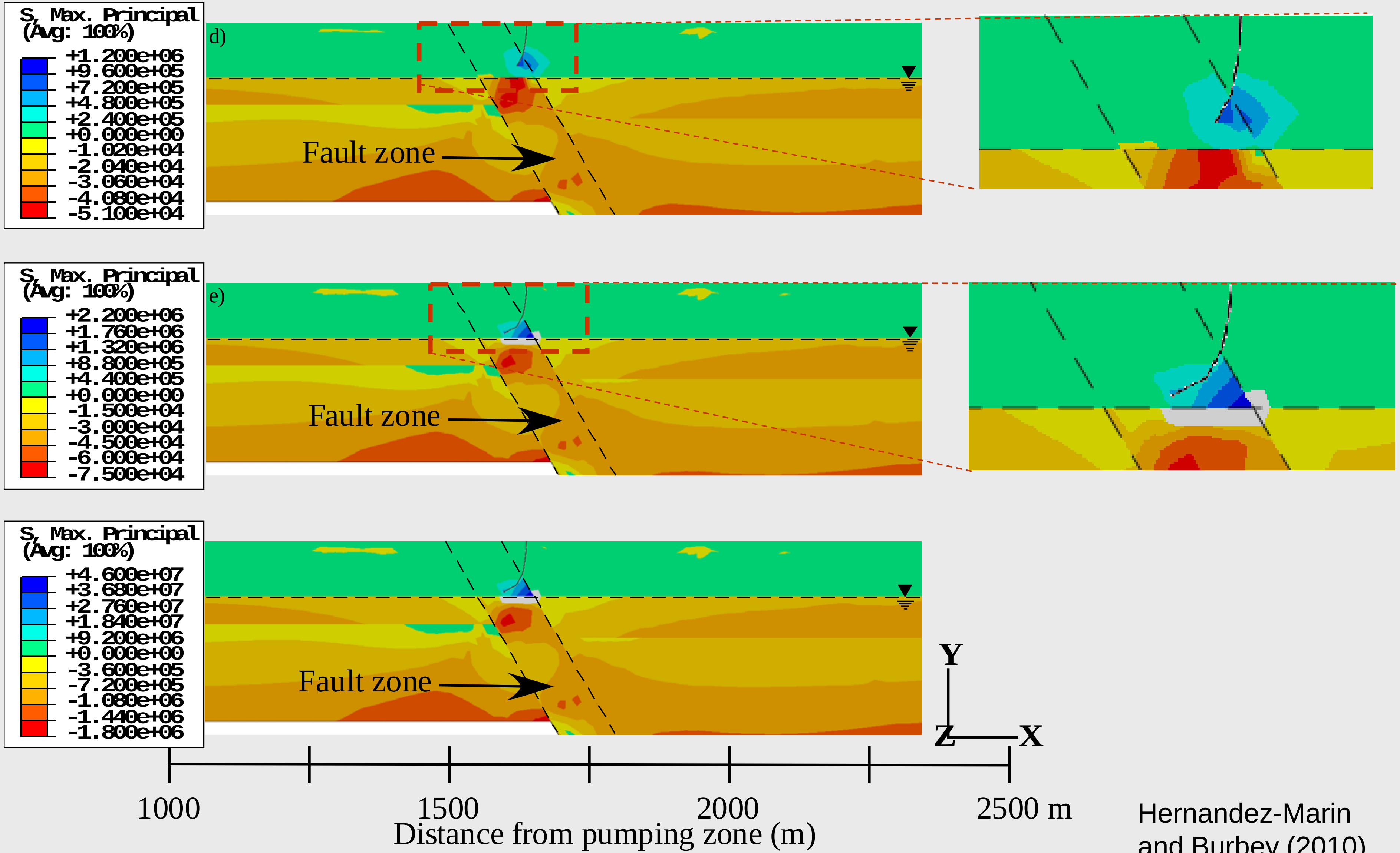
Fault Boundary

Stratigraphic conceptualization used in the following simulations



From Hernandez-Marin and Burbey, 2011

The location of the pumping zone and the change in the mechanical properties of the layers determine the path of the propagating fissure



Hernandez-Marin and Burbey (2010)

Water is the most essential element of life, because without water, you can’t make coffee

Nina Dobrev, 2014

Conclusions

- Aquifers experience vertical and horizontal deformation during pumping
- Accurate quantification of aquifer properties often requires the consideration of 3D deformation
- Horizontal and vertical surface deformations can be used to characterize aquifers and nearby faults