Geological Storage of CO_2 by Hubbert's Force Potential and Gravitational Groundwater Flow Systems

by

K. Udo Weyer, Ph.D., P.Geol., P.HG.
WDA Consultants Inc.
Calgary, Alberta, Canada
weyer@wda-consultants.com

Purpose

- Show that pressure gradients are not the driving forces for subsurface flow of groundwater and all other fluids.
- Show how gravitational groundwater flow affects the long term geological storage and subsurface migration of CO_2 and other fluids to the surface.

Common misconceptions in the treatment of subsurface fluid flow

- Water is incompressible
- Fluid flow is driven by pressure gradients
- Saltwater separates and sinks to the bottom of the system because of its higher density
- Aquitards ‘confine’ fluid movement to aquifers
- More water flows in aquifers than aquitards
- Recharge to artesian aquifers occurs only in outcrops
- Underground ‘buoyancy forces’ are always directed vertically upwards

Arrangement of presentation

- Driving Forces for Fluid Flow in the Subsurface
- ‘Buoyancy Forces’ = Pressure Potential Forces
- Groundwater Flow Systems
- Upward-Discharging Salt Water and Brine
- Crystal Geyser, Utah: Natural discharge of CO_2 into a River
- Downward-Directed Pressure Potential Forces: ‘Buoyancy Reversal’
- Trapping of CO_2 under Conditions of ‘Buoyancy Reversal’ and its Maintenance

Driving Forces for Fluid Flow in the Subsurface

Continuum Mechanics

Reservoir Engineering

(Muskat, 1937: velocity potential)

versus

Force Potential

Oil Exploration and Regional Groundwater Flow

(Hubbert, 1940, 1953, 1957)

Muskat's Velocity Potential Φ

Muskat, 1937: Φ = energy / unit volume; dimension $[L^2T^{-1}]$

$$\Phi = k/\mu\ (p - \rho g z)$$

Muskat, 1937, integrated the gravity as a vertical body force within the equation for velocity potential, making the equation unsuitable for 2D and 3D flow fields in anisotropic media.

Muskat's [1937] non-physical approach to fluid flow in the subsurface

$$\mathbf{v} = -(k/\mu)\, grad\, p$$

volumetric flow vector = **intrinsic permeability** / **dynamic viscosity** • **pressure gradient**

[Muskat, 1937, The Flow of Homogeneous Fluids Through Porous Media]

formerly known as "The Bible" of reservoir engineering

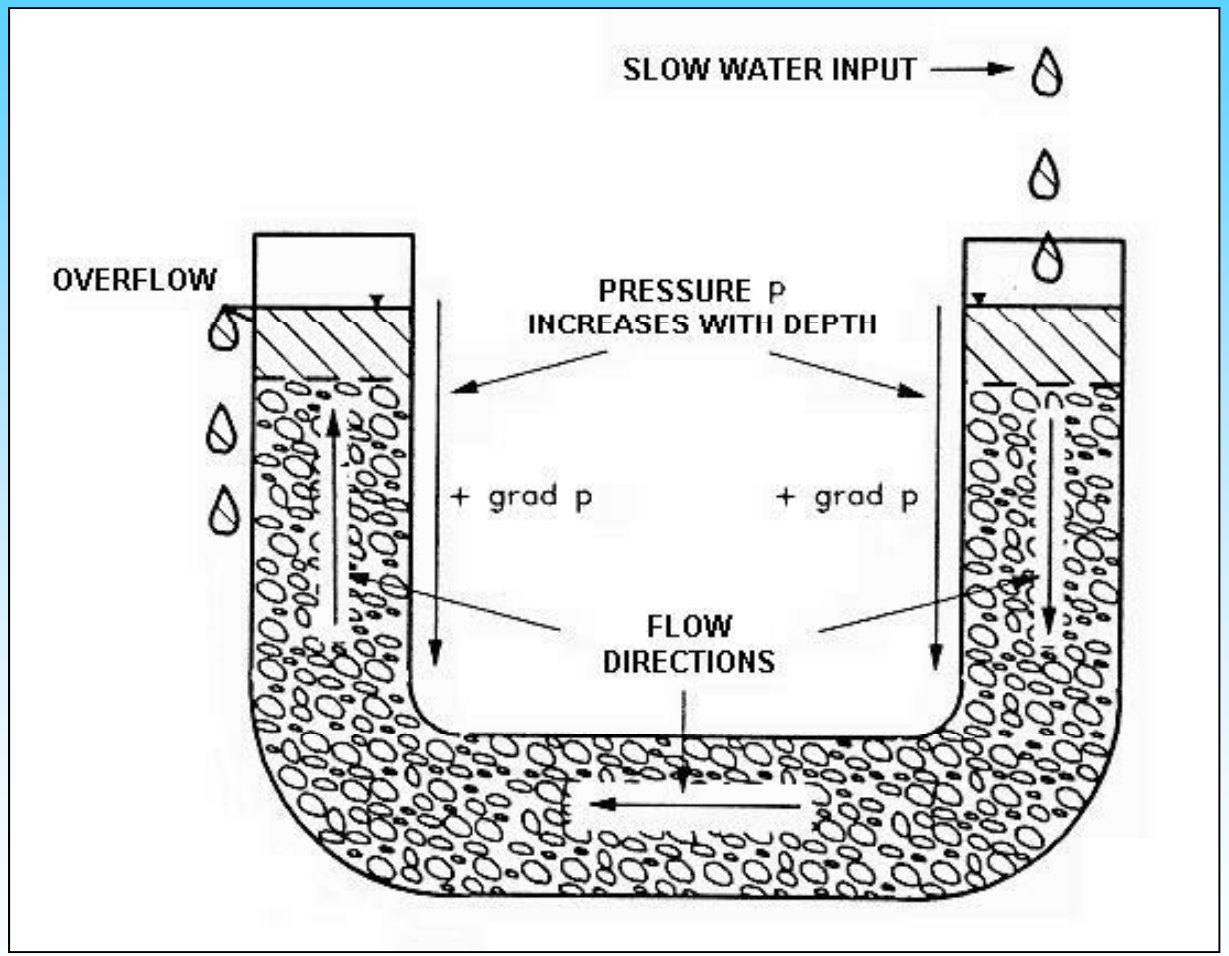
This is not a valid expression of Darcy's equation.

Darcy's Law [1856]

$$q = A * K * \Delta h$$

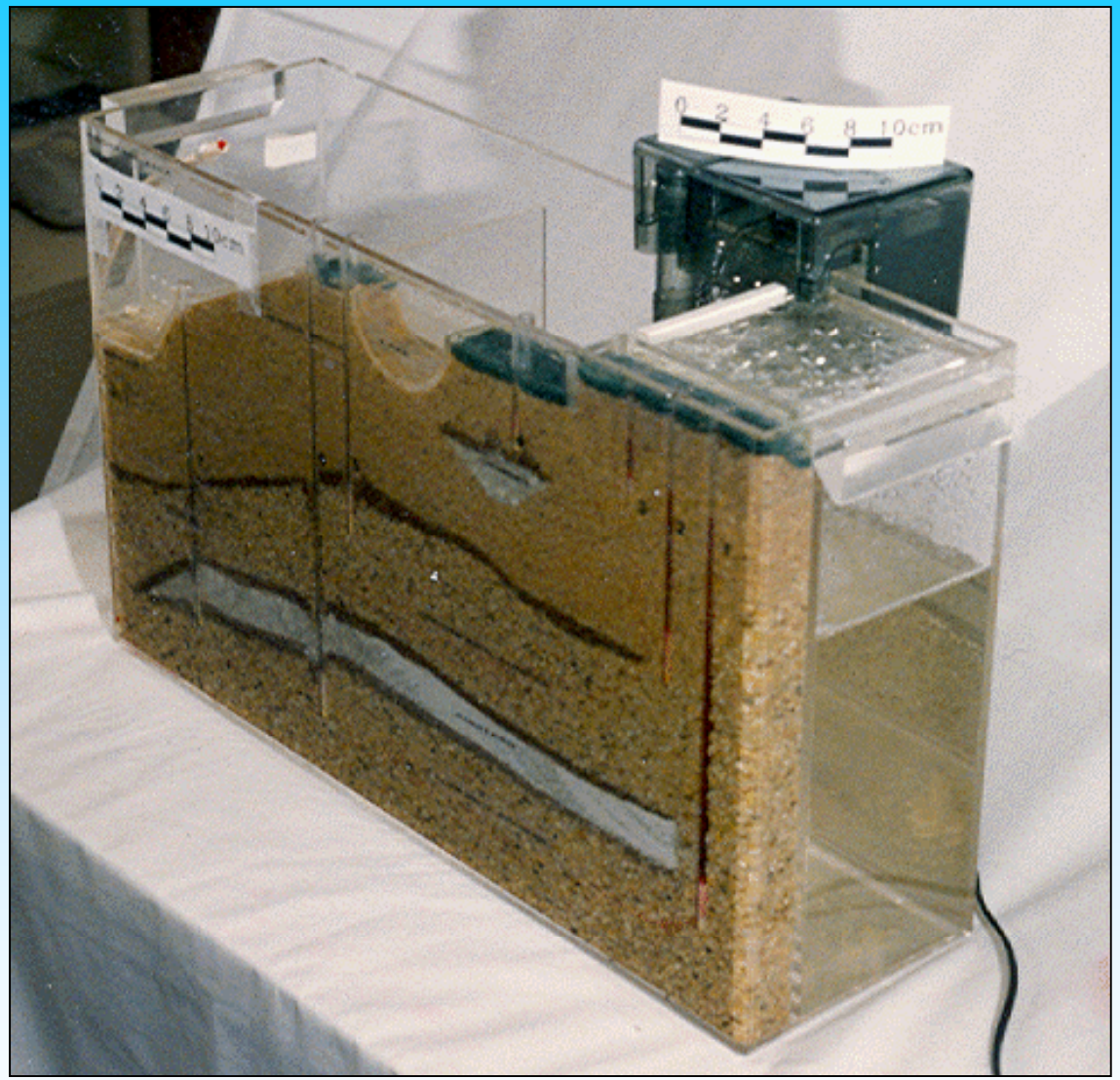
flow	=	area	•	hydraulic conductivity	•	head difference

Pressure gradients are not the motor for motion of fluids in the subsurface

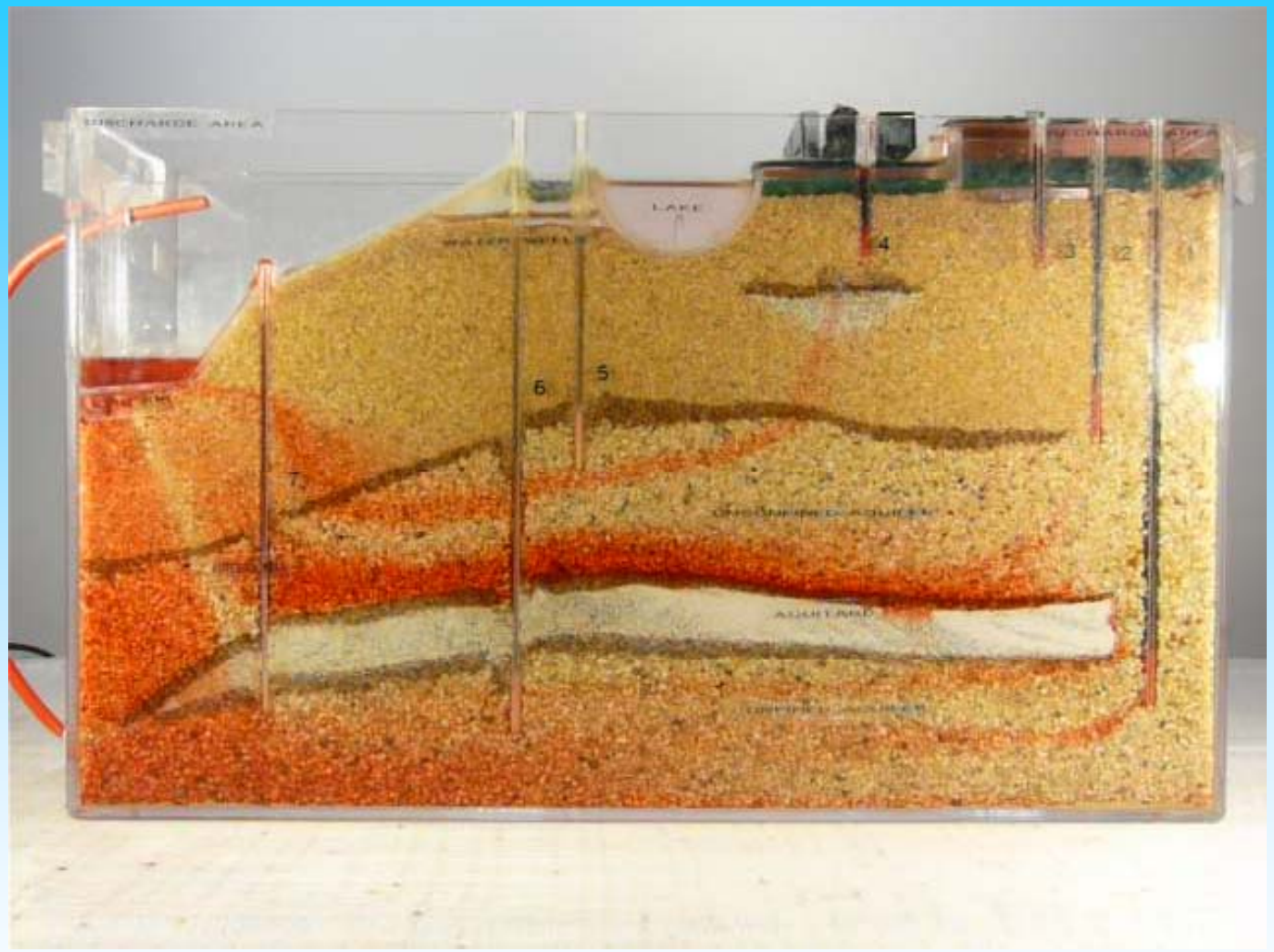


after Weyer, 1978

Water flows with and against the pressure gradients.



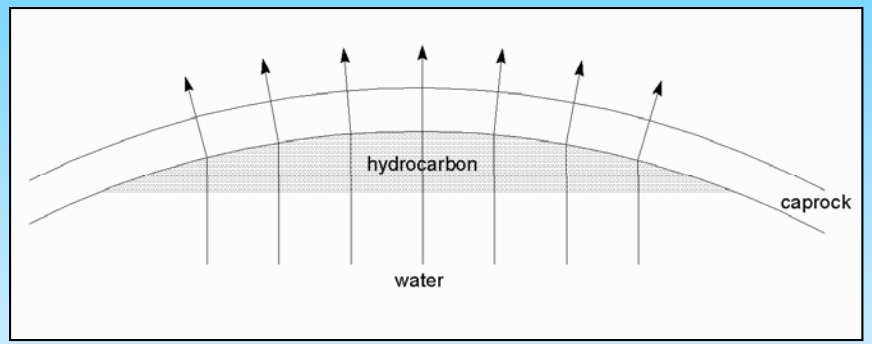
Sand model of groundwater flow



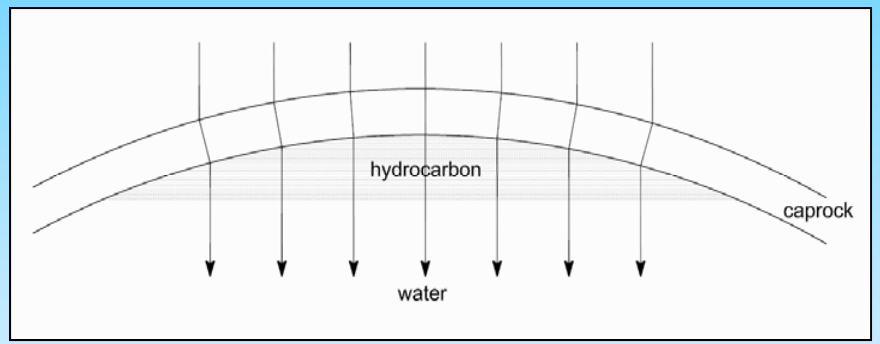
Demonstration of groundwater flow through geologic cross-section

For animation on the web see: **http://www.wda-consultants.com/sm-03.htm**

Schematic of water flow penetrating hydrocarbon (or CO_2) accumulations and caprock

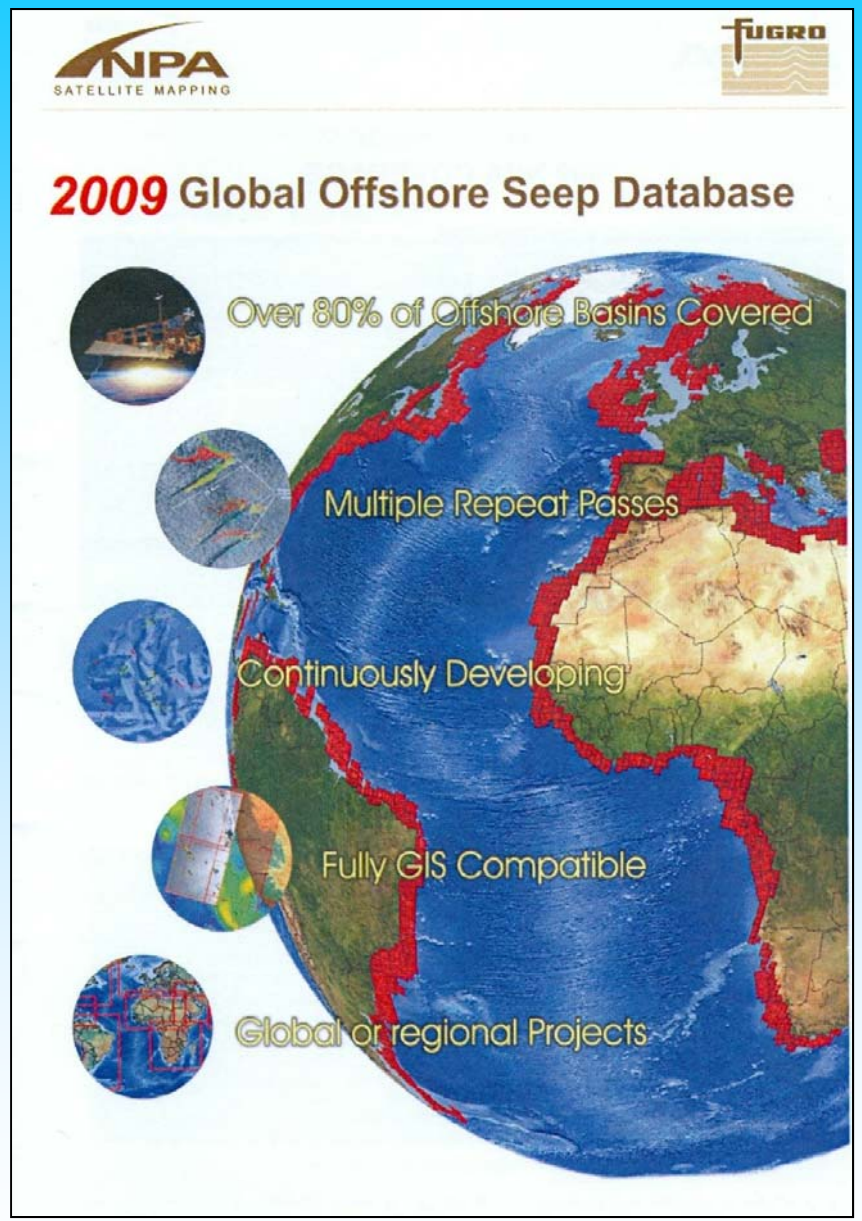


Upward Flow



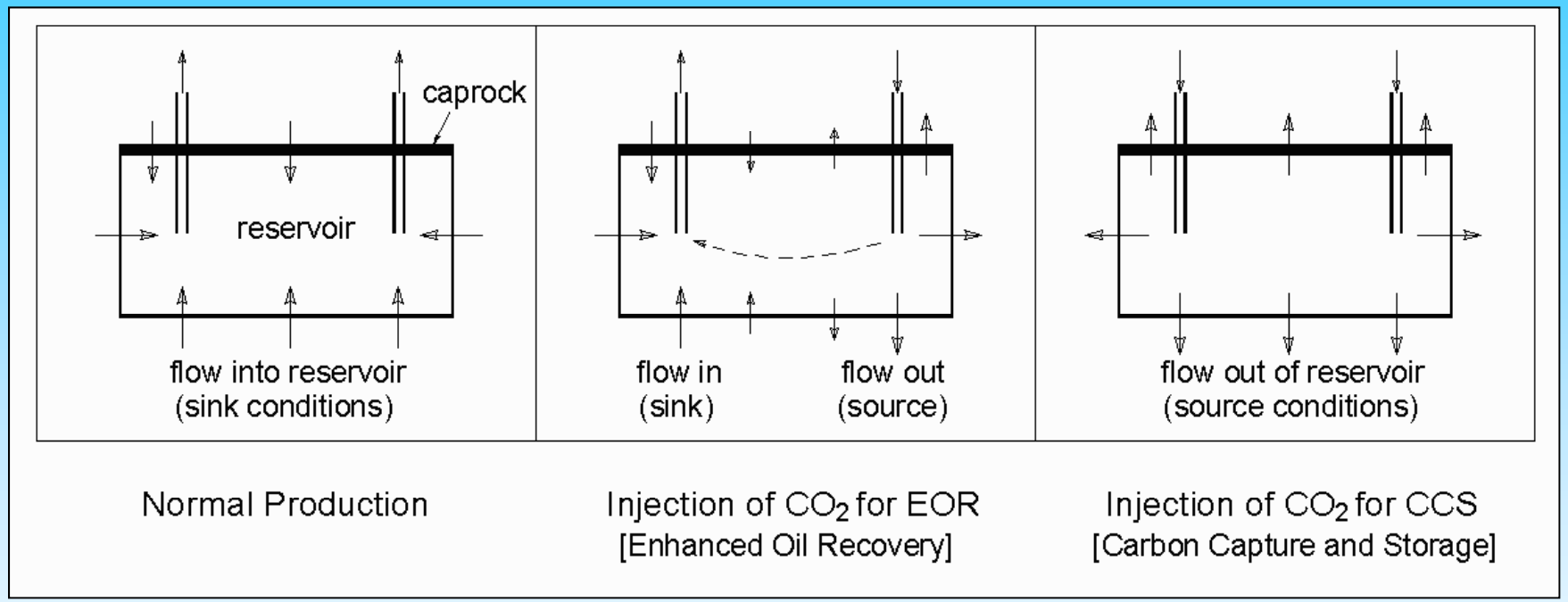
Downward Flow

A sandstone-shale boundary is an impermeable barrier to hydrocarbons or CO_2 trapped in the sandstone, but is not an impermeable barrier to the passage of water in either direction (see Hubbert, 1953, p.1975-1979).



Offshore hydrocarbon seeps are used in the exploration for offshore hydrocarbon fields, much the same way as they used to be applied in the early days of onshore hydrocarbon exploration.

The assumption that hydrocarbon fields are safe areas for CO_2 storage is therefore not *a priori* correct, but needs to be proven in each particular case.



Changes of sink towards source conditions within a reservoir during petroleum production, EOR and subsequent CCS

Continuum Mechanics vs. Force Potential

Continuum Mechanics	Force Potential
• Oil Industry: Reservoir Engineering	• Oil Industry: Exploration Geologists General: Groundwater Flow Systems
• Source: Muskat, 1937	• Source: Hubbert, 1940,1953,1957,1969
• p = energy / unit volume [$ML^{-1}T^{-2}$]	• Φ = energy / unit mass [L^2T^{-2}]
• hydraulic forces: grad p	• hydraulic forces: grad Φ
• area considered: reservoirs only	• area considered: all rocks from groundwater table to selected depth, including reservoirs

The methods of Hubbert's Force Potential should be applied to Carbon Sequestration

Application of Hubbert's Force Potential to Groundwater Flow

$$\Phi = \Phi_g + \Phi_p$$

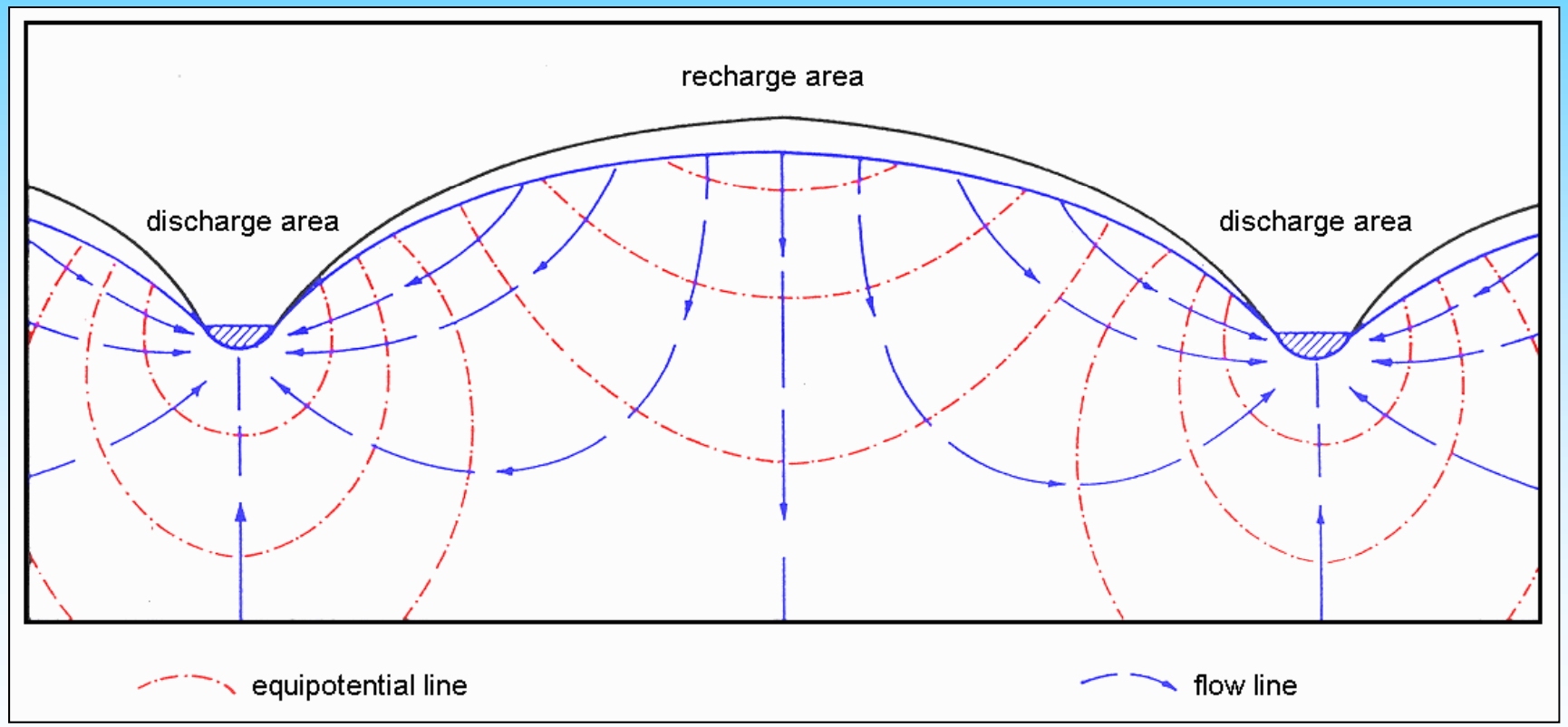
Potential = Energy / Mass [L^2T^{-2}]

$$-grad\ \Phi = \vec{g} - \frac{grad\ p}{\rho}$$

forces = -grad Φ

Hubbert, 1940: Theory of groundwater motion
Hubbert, 1953: Entrapment of petroleum under hydrodynamic conditions
Hubbert, 1957: Darcy's law and the field equations of the flow of underground fluids

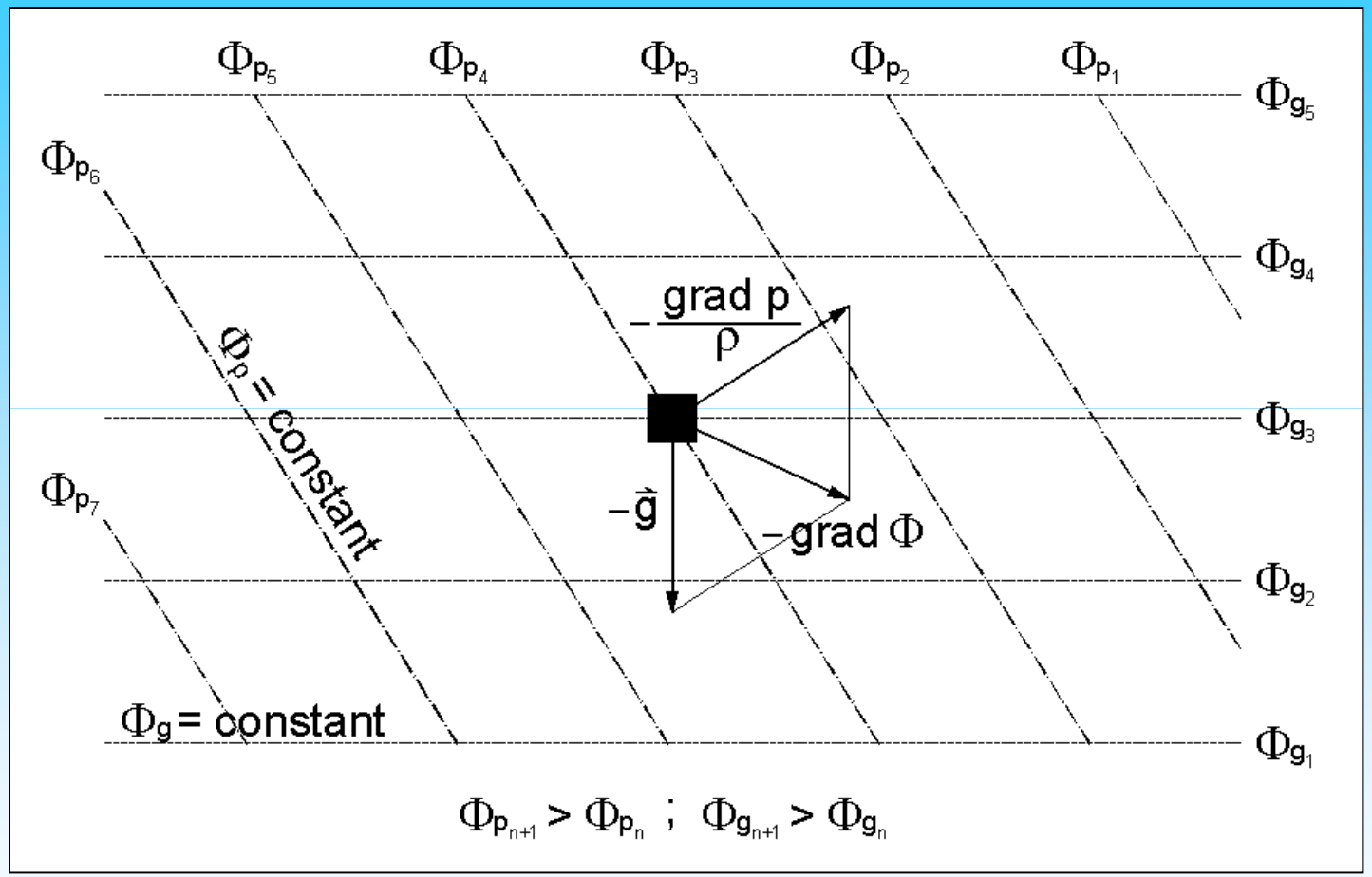
Hubbert's [1940] Schematic Diagram of Gravitational Groundwater Flow



after Hubbert, 1940

Under natural conditions, the fresh water energy field of hydraulic potentials determines the state of energy for all fluids in the subsurface [Hubbert, 1953], for groundwater, salt water, oil, gas, and CO_2

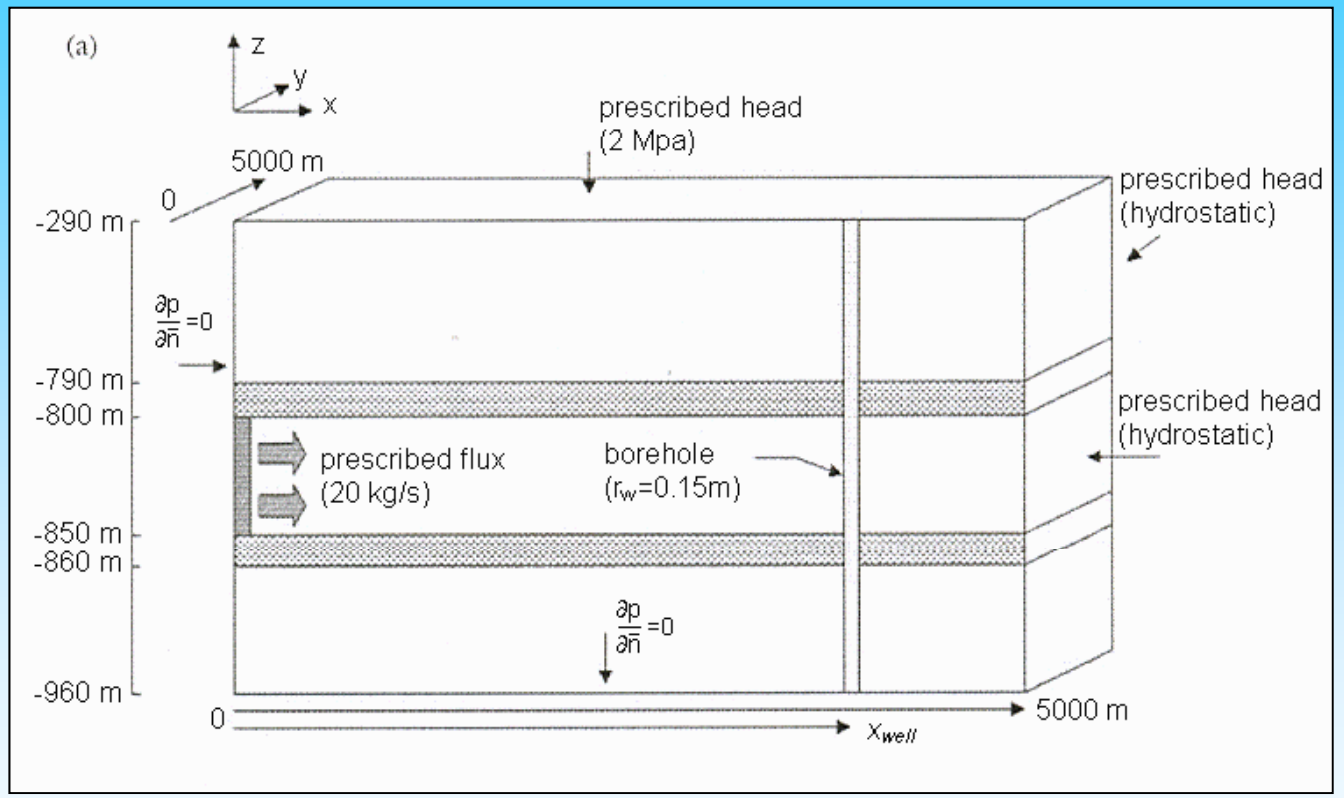
Vectoral addition of hydraulic forces



after Weyer, 1978

The direction of the total hydraulic force is fundamentally different from the direction of the pressure potential force

The Princeton model on leaking abandoned wells in Alberta



from Scherer, G.W., M.A. Celia, J-H. Prévost, S. Bachu, R. Bruant, A. Duguid, R. Fuller, S.E. Gasda, M. Radonjic, and W. Vichit-Vadakan, 2005, 2005, Figure 3a

- The model is based on pressure and the assumption of hydrostatic conditions. Potentials (energy/mass) and gravitational forces are thereby not taken into account
- Forces are: “pressure drive and buoyancy” [Scherer et al., 2005, p.828]
- Gravitational groundwater flow systems are not incorporated

Mathematical models by IPCC, 2005: restricted to capillary and buoyancy forces

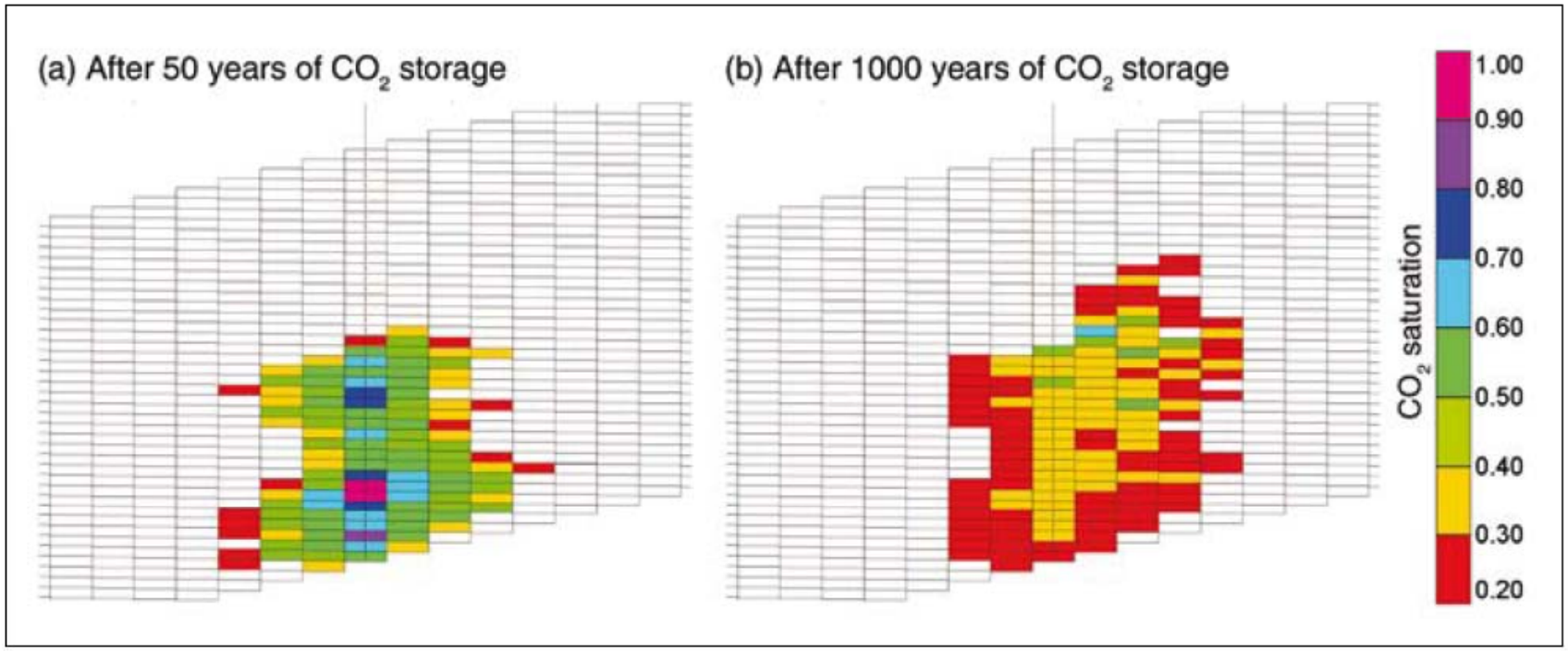


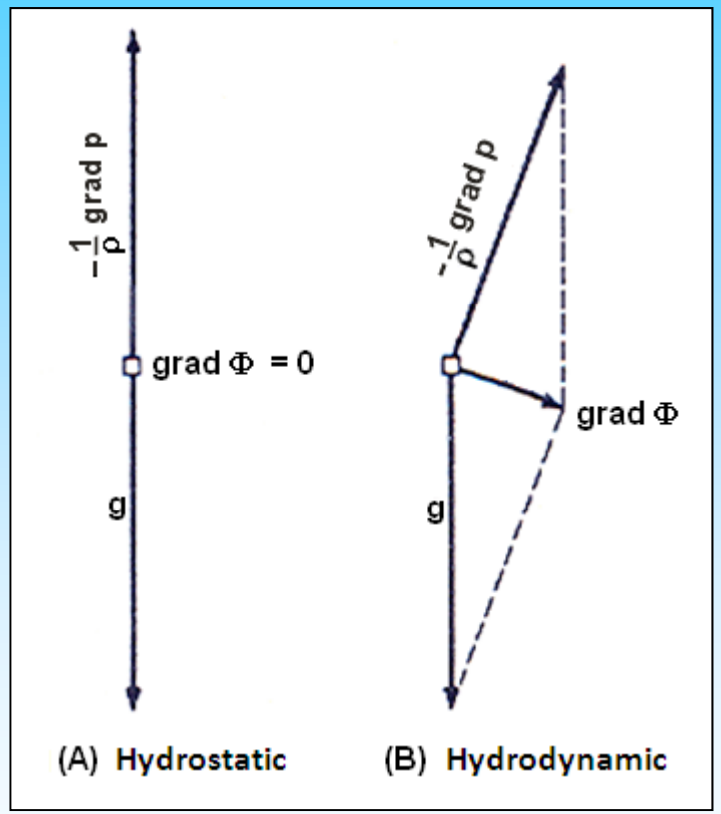
Figure 5.8 Simulation of 50 years of injection of CO_2 into the base of a saline formation. Capillary forces trap CO_2 in the pore spaces of sedimentary rocks. (a) After the 50-year injection period, most CO_2 is still mobile, driven upwards by buoyancy forces. (b) After 1000 years, buoyancy-driven flow has expanded the volume affected by CO_2 and much is trapped as residual CO_2 saturation or dissolved in brine (not shown). Little CO_2 is mobile and all CO_2 is contained within the aquifer (after Kumar et al., 2005).

IPCC, 2005

The above models ignore gravitational groundwater flow systems, and, by their caption, misrepresent buoyancy forces and possibly also capillary forces. Size of model area not indicated.

‘Buoyancy Forces’ = Pressure Potential Forces

Hydraulic forces (grad Φ) under hydrostatic and hydrodynamic conditions

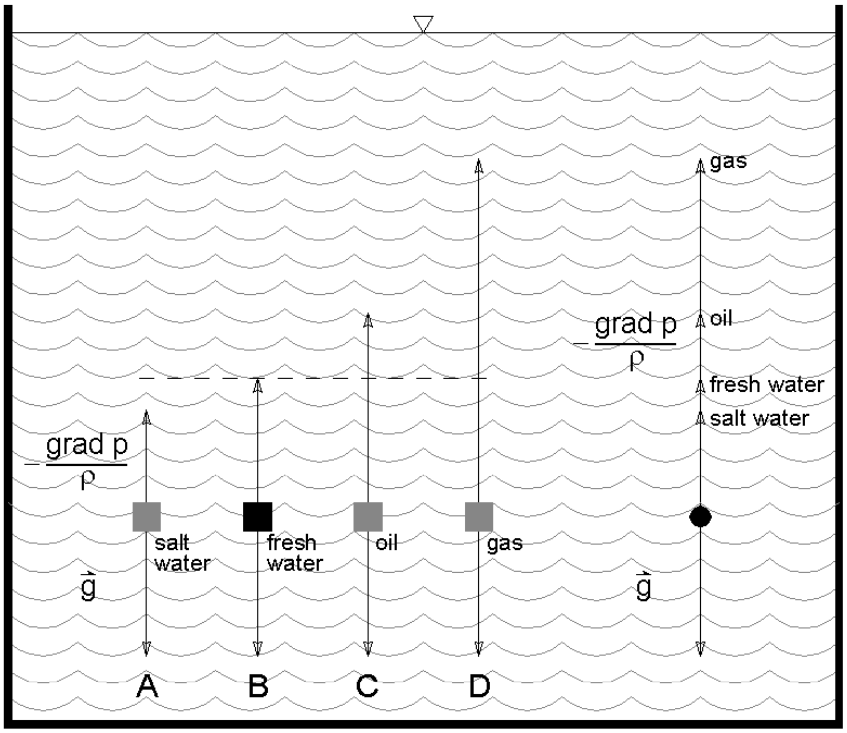


after Hubbert, 1953: Entrapment of Petroleum Under Hydrodynamic Conditions, Fig. 4

There is no principle difference between hydrostatic and hydrodynamic forces. Hydrostatic conditions (A) are a special hydrodynamic condition wherein the pressure potential gradient is equal in size to the gravitational force, but pointing in the opposite direction. Hence, the hydraulic forces Φ are equal to 0 and the water does not flow.

Under hydrodynamic conditions (B), the water flows and the fresh water pressure potential gradient is either not pointing in opposition to the gravitational gradient g, or is of different magnitude.

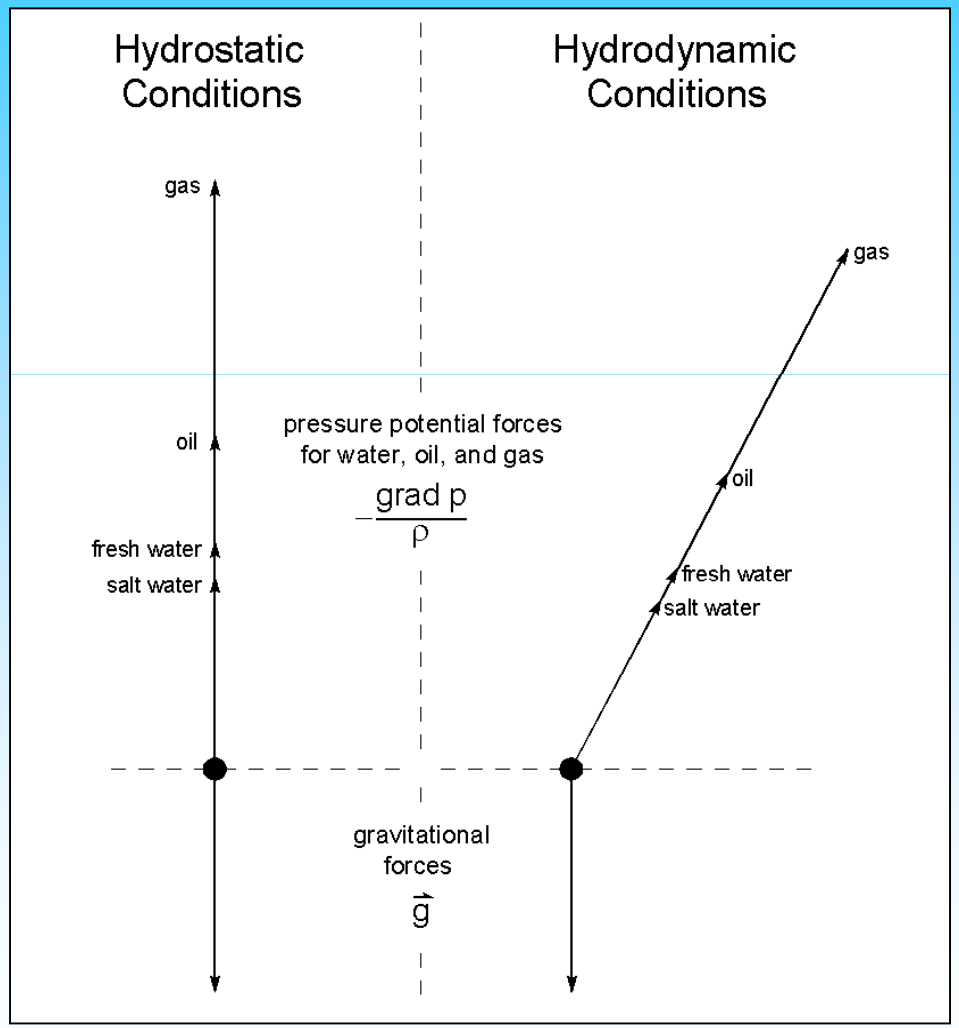
Schematic derivation of pressure potential forces ('buoyancy forces') for oil, gas, and salt water under hydrostatic conditions



A = downward flow for dense salt water.... $(\text{grad } p)/\rho < \vec{g}$
B = no flow of fresh water..... $(\text{grad } p)/\rho = \vec{g}$
C = upward flow for oil..... $(\text{grad } p)/\rho > \vec{g}$
D = upward flow for gas..... $(\text{grad } p)/\rho > \vec{g}$

- Submerged salt water, fresh water, oil and gas show different pressure potential gradients as shown in the diagram
- The salt water has a greater density than fresh water and sinks vertically downwards
- Submerged fresh water does not move up or downwards in a hydrostatic fresh water field
- Oil and gas have lower density than fresh water and float vertically upwards
- The combined force vectors on right side of the diagram combine the pressure potential forces of fresh water, oil, and gas. They are all directed vertically upwards because the fresh water pressure potential force is directed vertically upwards. The direction of the fresh water pressure potential force determines the direction of the pressure potential forces for oil and gas. That is the reason why oil and gas float vertically upwards under hydrostatic conditions.
- **Exactly the same happens under hydrodynamic conditions, except that the direction of the fresh water pressure potential force usually takes a non-vertical direction in space.**

Comparison of the direction of pressure potential forces ('buoyancy forces') under hydrostatic and hydrodynamic conditions



- The hydrostatic part of the diagram shows the pressure potential vectors to be directed vertically-upwards while the hydrodynamic part of the diagram shows a non-vertical direction of pressure potential vectors for all fluids: fresh water, salt water, oil, and gas.
- The direction of any so-called 'buoyancy force' is determined by the direction of the pressure potential force of fresh water which, under hydrodynamic conditions, may point in any direction in space.
- Division of the water pressure potential force by the density of the 'buoyant' fluid determines the size of its pressure potential force.
- The flow direction of the 'buoyant' fluid is determined by vectoral addition of the 'buoyant' pressure potential force and the gravitational force as shown in the next slide.

Determination of flow directions for all fluids in the subsurface

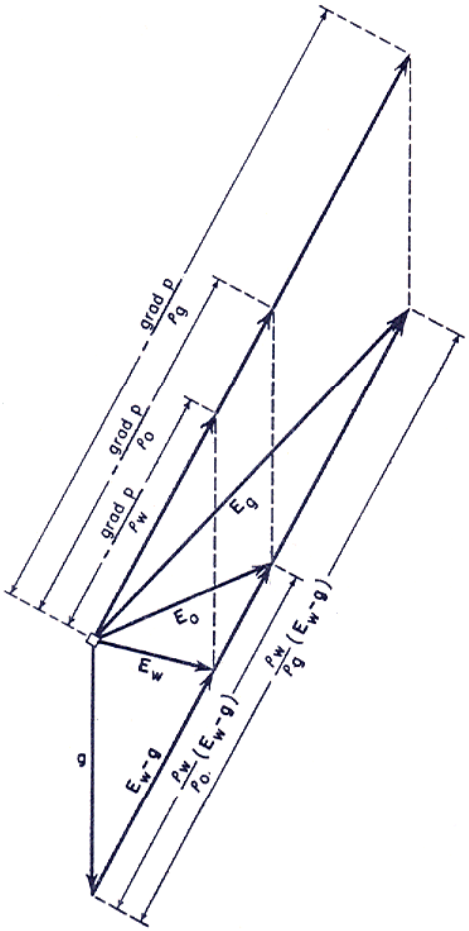
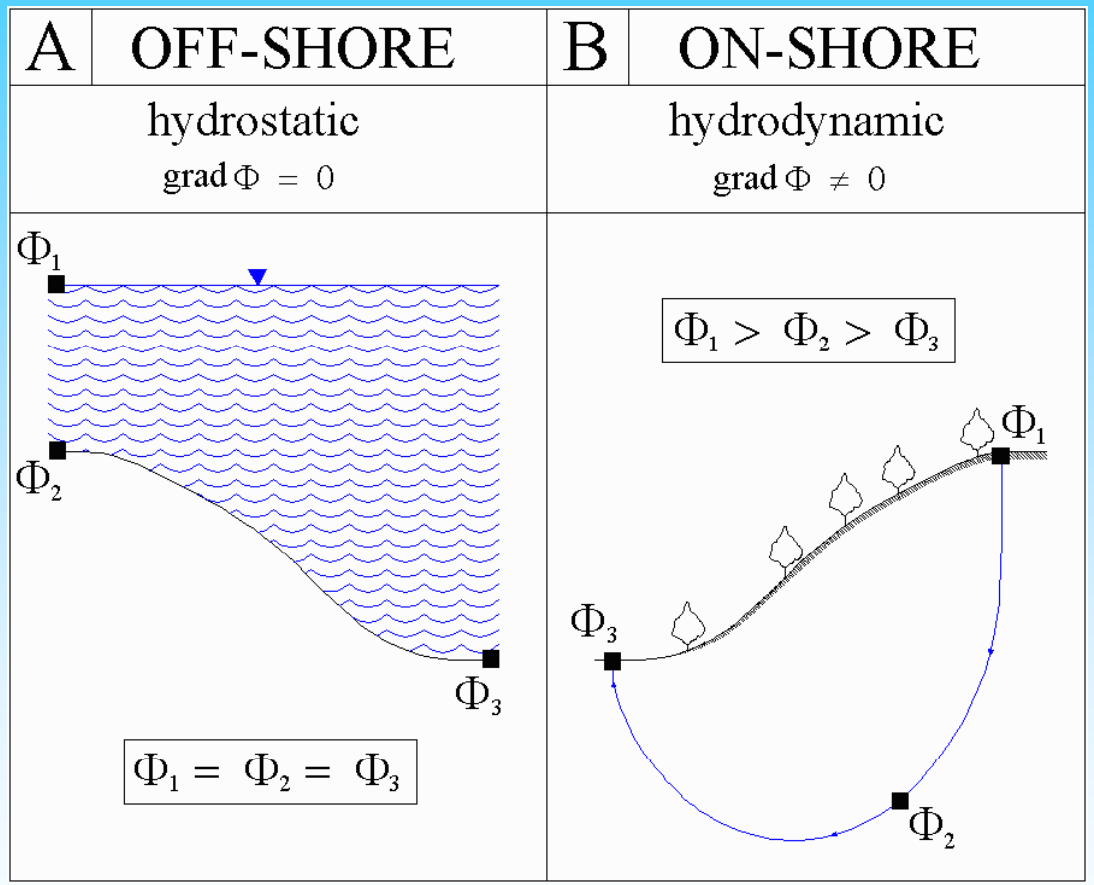


FIG. 16.—Impelling forces on water, oil, and gas in hydrodynamic environment.

Hubbert, 1953: Entrapment of Petroleum Under Hydrodynamic Conditions

- The pressure potentials of fresh water determine the pressure potentials for all other fluids (oil, gas, CO_2, salt water) within the ubiquitous energy field created by fresh groundwater
- The lower densities of oil and gas cause stronger pressure potential forces to maintain, within the freshwater field, the same energy status for the less dense fluids. The pressure potential force of water is divided by the densities for oil and gas.
- Vectoral addition in turn leads to significantly differing flow directions within the same energy field as shown.
- Liquid CO_2 has a density similar to that of oil at about 0.85 g/cm^3.
- Salt water gradients were not shown in the diagram by Hubbert. Slide 39 shows that ocean-type salt water has almost the same flow direction as fresh water.

Comparison of hydrostatic and hydrodynamic conditions in subsurface fluid flow.

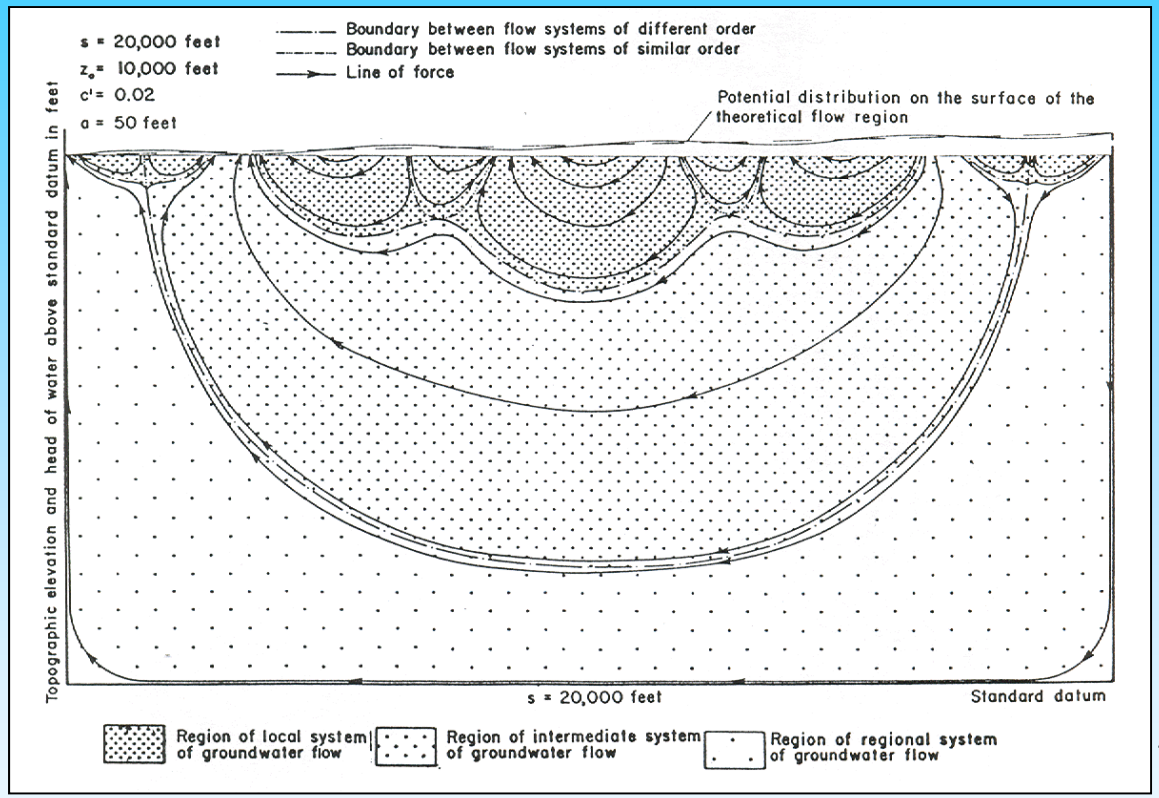


Φ : hydraulic potential

grad Φ : hydraulic force

Groundwater Flow Systems

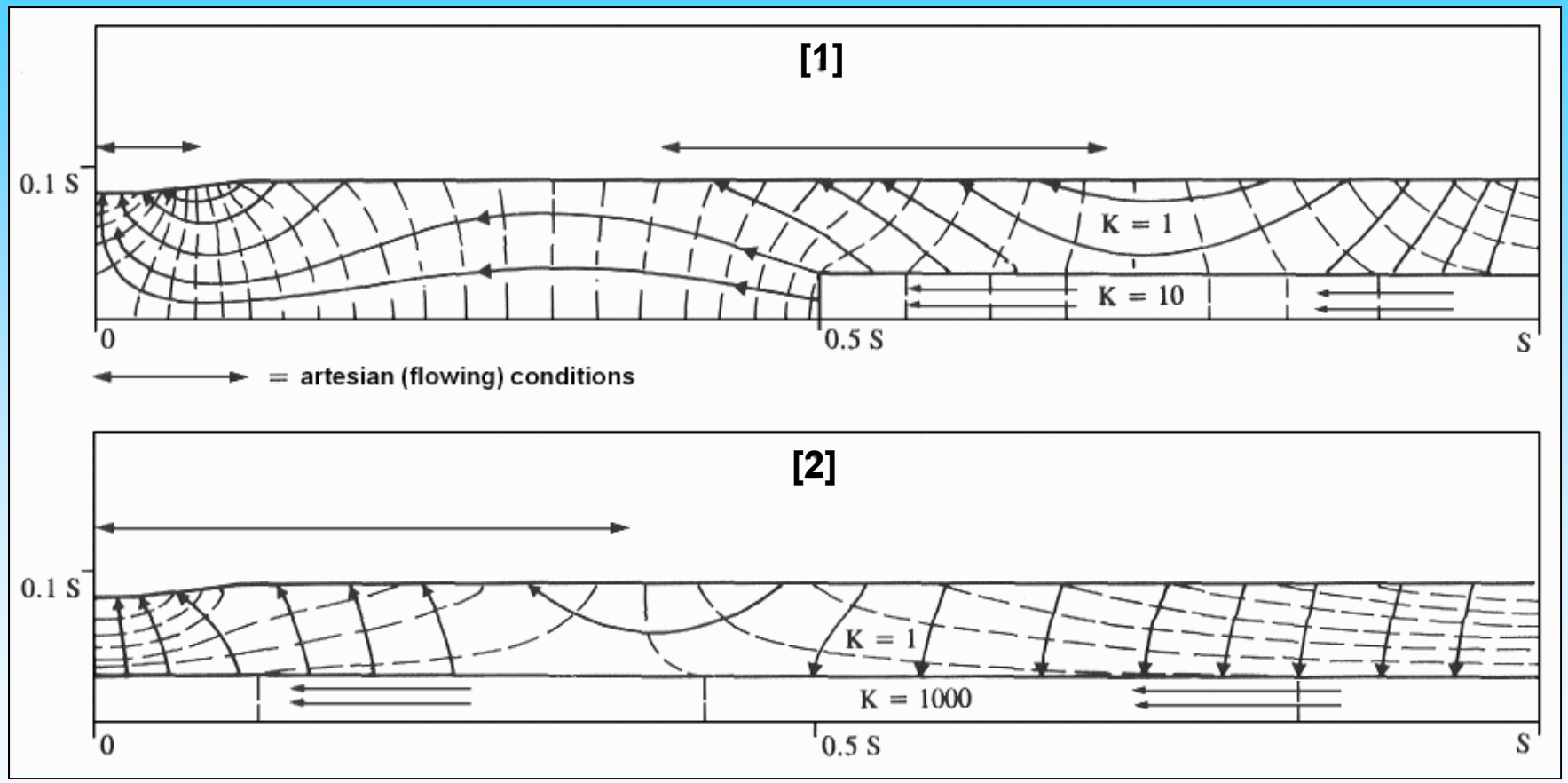
Tóth's [1962] analytical calculation of groundwater flow systems in a cross-section with homogeneous and isotropic lithology



Tóth, 1962

Total elevation gain is approximately 150 m over about 6 km; the amplitude of hills is approximately 15 m; penetration depth of local groundwater flow systems is up to 900 m, intermediate groundwater flow system about 2400 m, and regional groundwater flow system over 3000 m (lower border limited by model depth).

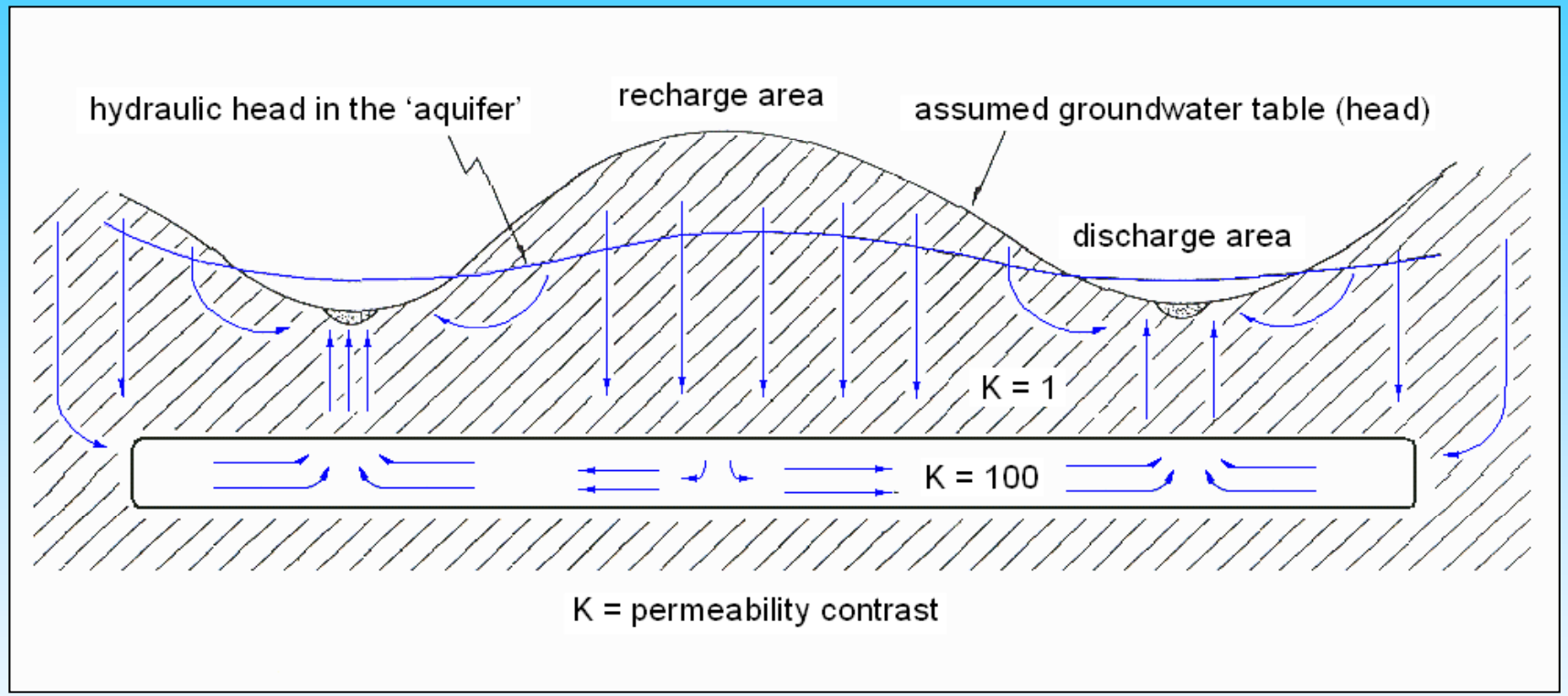
Effect of buried higher-permeable layer upon groundwater flow pattern and location of recharge and discharge areas



after Freeze and Witherspoon, 1967

Under natural conditions, twice as much water can flow within the aquitard (downward and upward flow) as compared to the aquifer (lateral flow). (See case [2].)

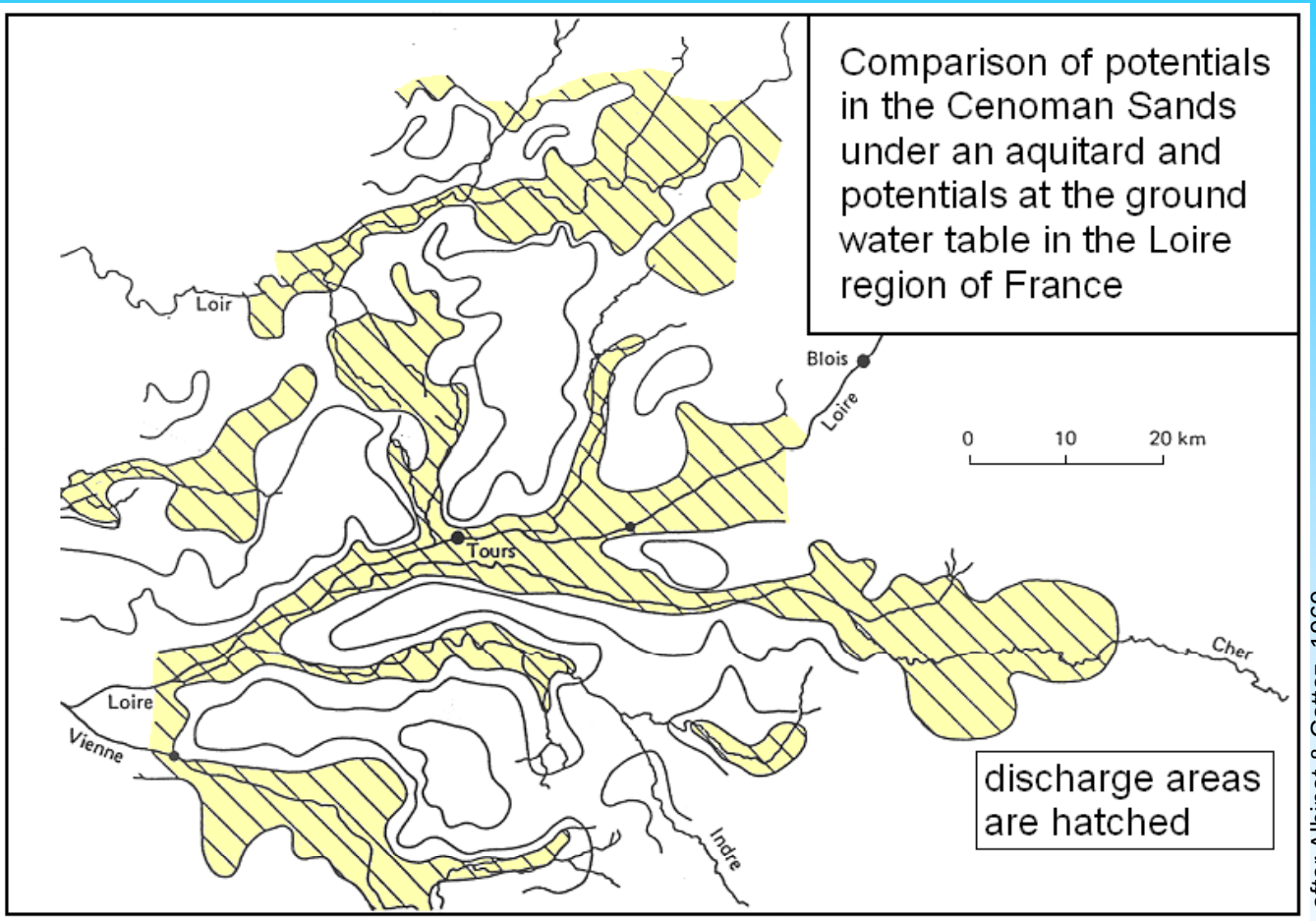
Schematic diagram of groundwater flow with aquitard over buried aquifer



after Weyer, 1996

Twice as much groundwater flows through the aquitard (vertically downwards and upwards) as through the aquifer (laterally). The head distribution in the aquifer is a replica of the topography. In recharge areas the potential in the aquifer is lower than that at the groundwater table, in discharge areas the potential in the buried aquifer is higher than that at the groundwater table.

Plan view of groundwater flow systems penetrating an aquitard



after Albinet & Cottez, 1969

Recharge and discharge areas are outlined by differences in hydraulic heads (water levels) in piezometers. Subtracting head values in the aquifer from those at the groundwater table. Negative values indicate areas of upward flow through aquitard and discharge. They are hatched and shown in yellow.

Erroneous assumptions about regional groundwater flow 1

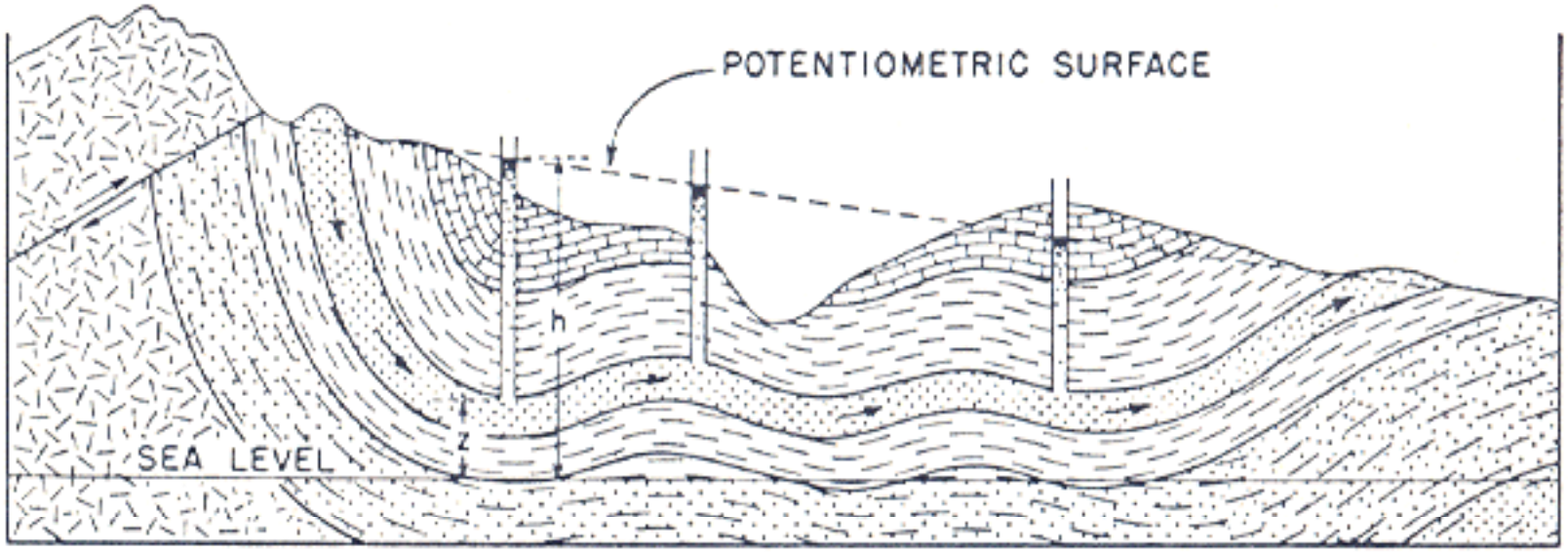
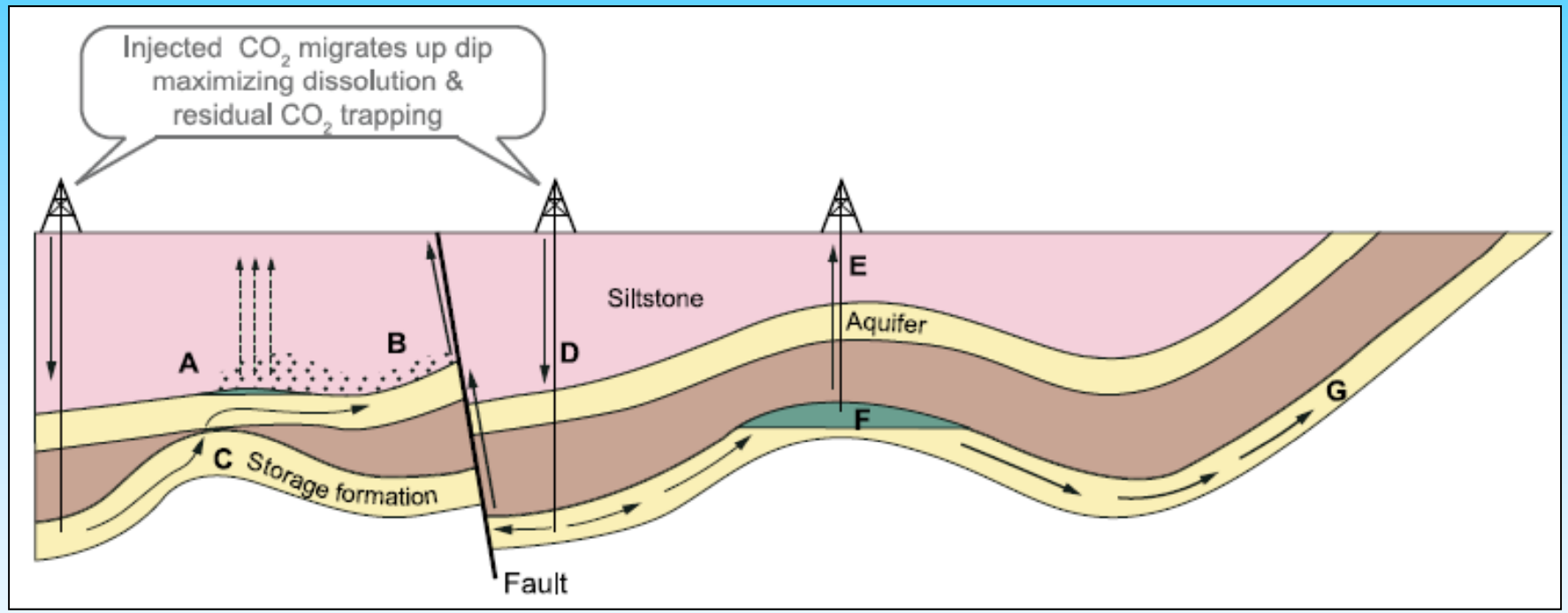


FIG. 11.—Regional flow of water through sand from higher to lower outcrop, showing continuous drop in potential.

Hubbert, 1953: Entrapment of Petroleum Under Hydrodynamic Conditions

Hubbert restricted flow to the aquifer. Knowledge about groundwater flow systems penetrating aquitards only became available more than a decade later (Freeze and Witherspoon, 1966, 1967).

Erroneous assumptions about regional groundwater flow 2



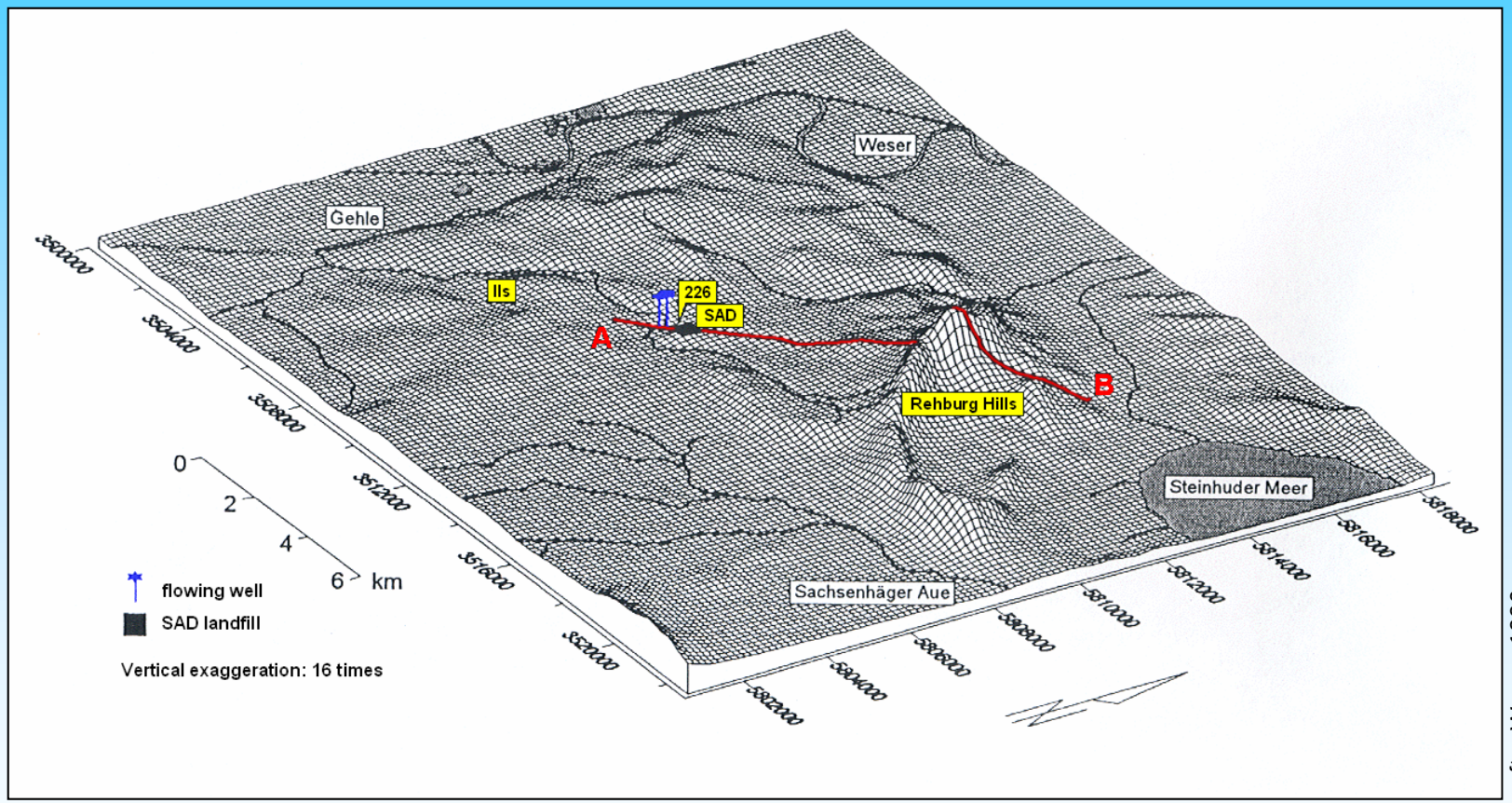
After IPCC Special Report on Carbon Dioxide Capture and Storage, 2005, Figure 5.25

IPCC, 2005 missed Tóth's (1962) paradigm shift, and the associated groundwater flow through aquitards, about forty years after its publication. It also refers to the outdated concept of up-dip migration.

Upward-Discharging Salt Water and Brine

Case 1: Münchehagen landfill [SAD], Germany

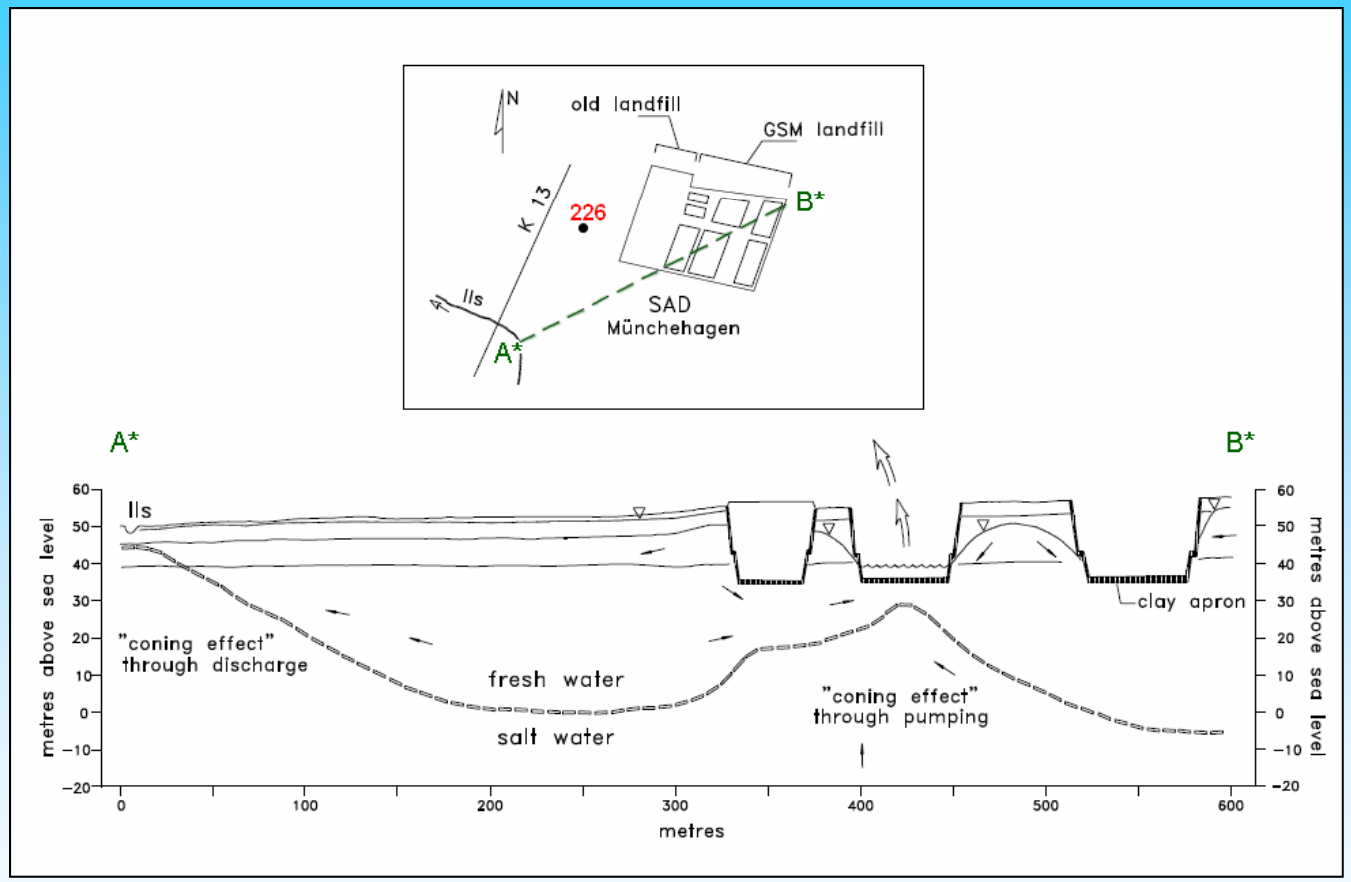
Digital Elevation Model [DEM]



after Weyer, 1996

The DEM shows the position of the cross-section A-B, the Rehburg Hills, the landfill (SAD), borehole 226, and the river Ils. The size of the DEM is about 22 km (E-W) by about 18 km (N-S).

Discharge of saline water at the Ils river (natural discharge) and at the Münchehagen landfill site (pumping-induced coning).



after Lüdeke, 1987

Investigators at the site discovered what they called a “coning effect” for salt water of ocean-type salinity. They did not realize that the connection to the Ils river was natural discharge of saline water and the flow towards the landfill was pumping-induced discharge. Note location of borehole 226 in inset.

2D-vertical model of groundwater flow directions in cross-section A-B in the Münchehagen landfill area

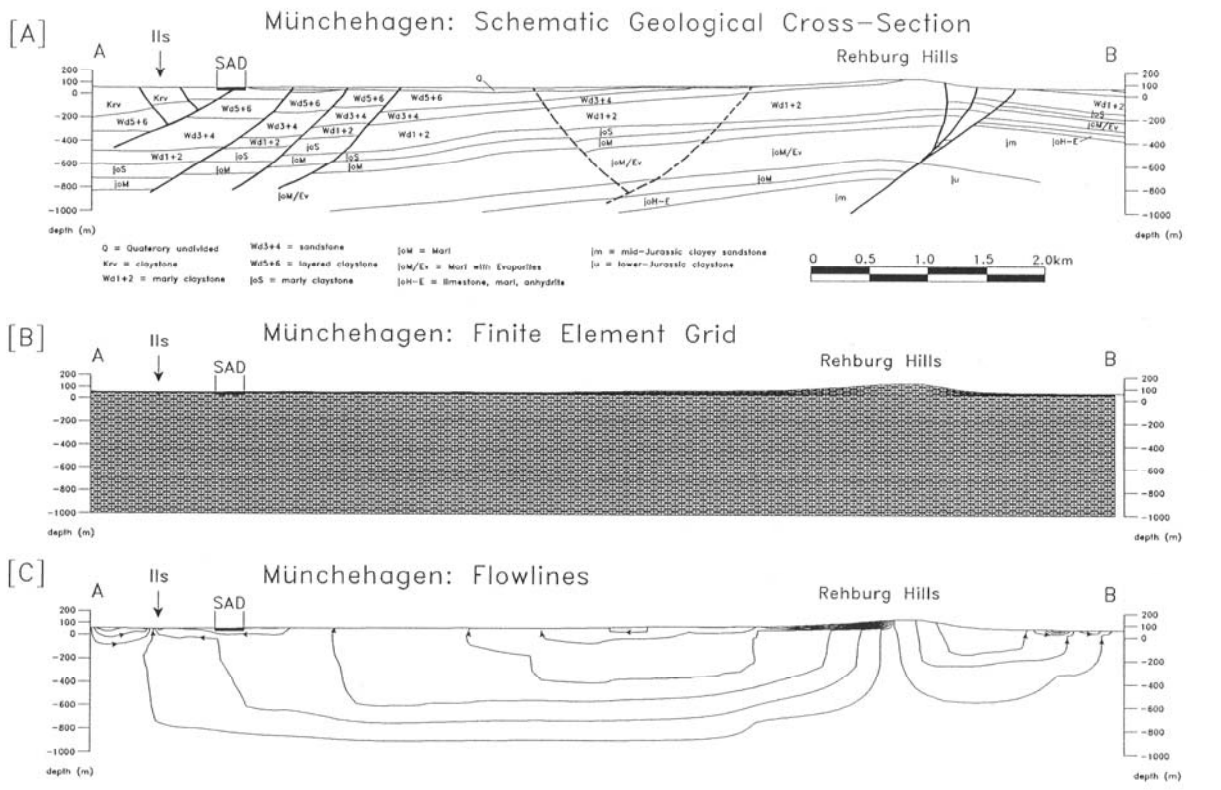
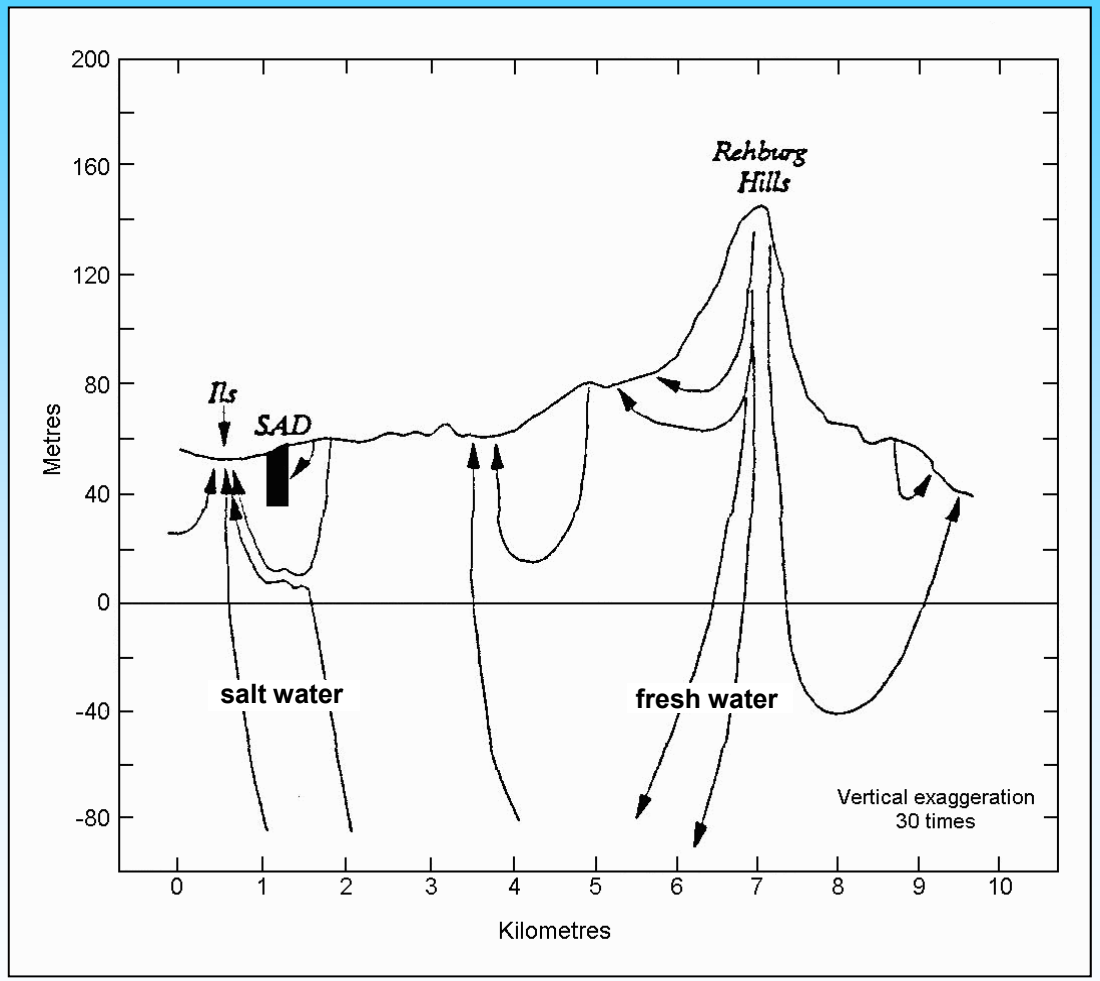


Fig. 3 A: Geological cross-section A-B (see Fig. 1). The geological profile was composed based on data from Jordan (1975) and Rohde (1992). B: Finite element grid for geological cross-section A-B. C: Vertical groundwater flow model Münchehagen: Flow lines in geological cross-section A-B. Vertical exaggeration is 1:1.

after Weyer, 1996

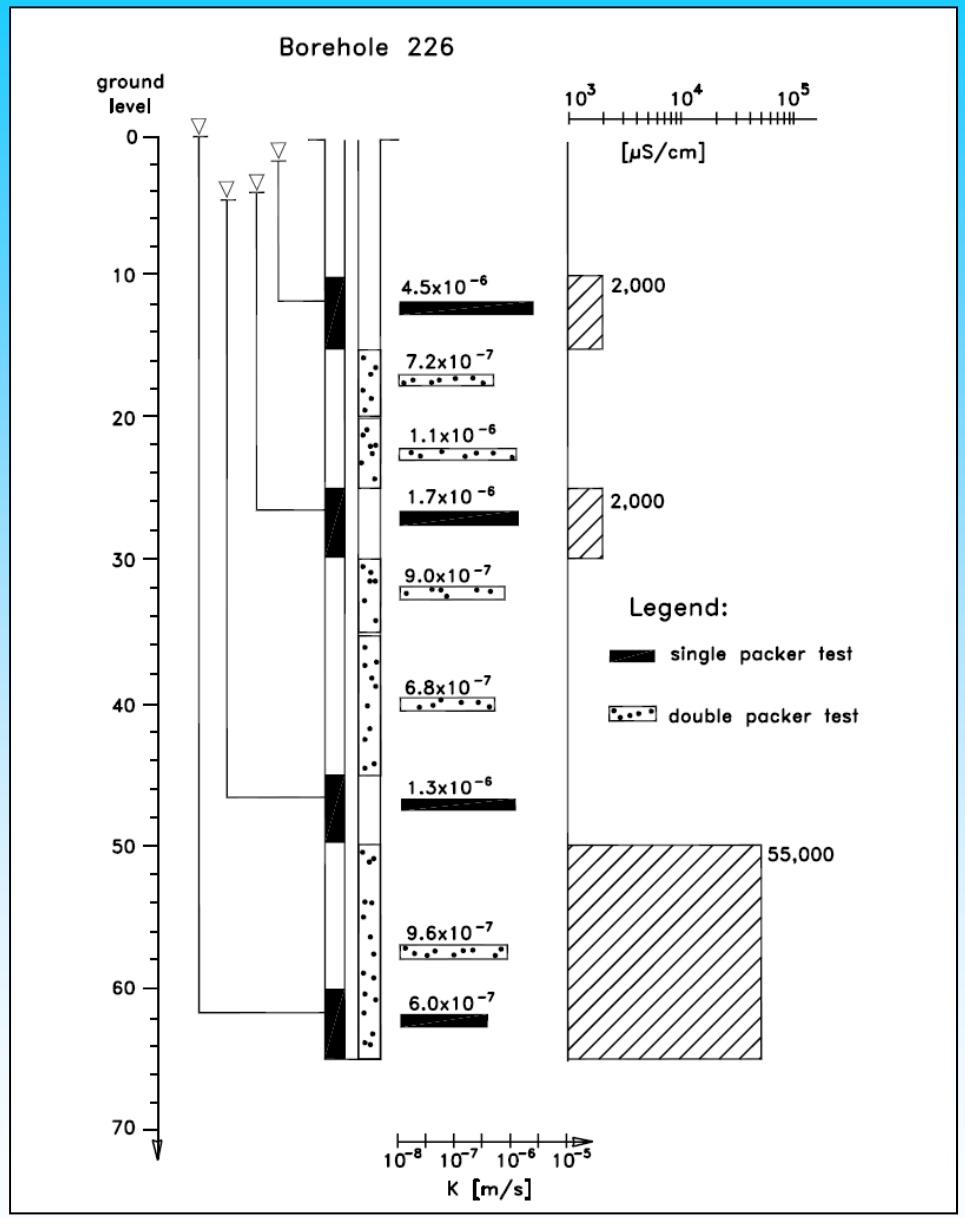
Geologic cross-section taken from 1:25,000 geologic maps. Calculated groundwater flow directions were based on the groundwater table (following topography) and estimated permeability contrasts.

Cross-section A-B showing flow lines calculated by 2D-vertical mathematical model



after Weyer, 1996

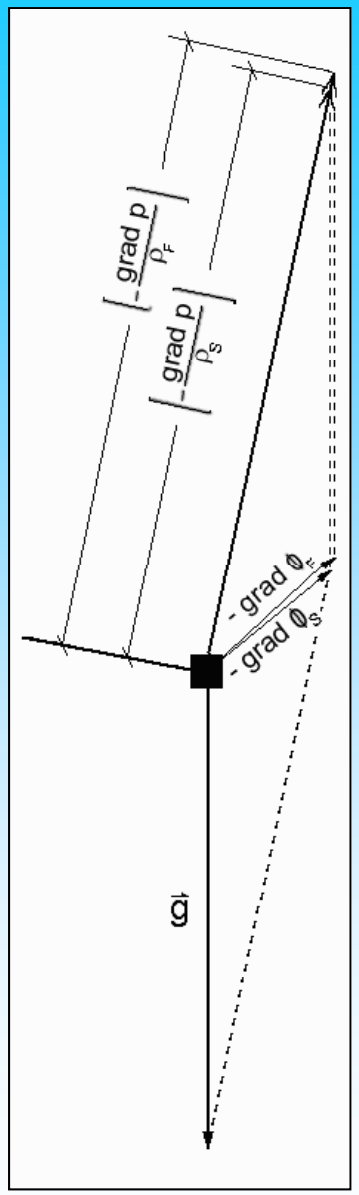
- SAD = Münchehagen landfill
- Laterally-compressed flow lines as returned by model calculation; vertical exaggeration 30:1
- One of the two upward flow lines of saline water enters the river Ils directly. The other passes beneath the SAD landfill at 50 m depth below ground.
- Due to higher permeable layer, lateral flow of shallow and deep flowlines converge towards river Ils.



Occurrence of saline water in borehole 226 at a depth of about 50 m below ground.

- Conductivity and salinity of the saline water is about that of ocean water.
- Upward flow of saline water to about 50 m depth due to higher permeable layer above that depth (see permeability distribution in diagram: 1.3 x 10^{-6} m/s vs 6.8 x 10^{-7} m/s).
- Due to this higher-permeable layer, lateral flow of shallow and deep flow lines converge and flow towards the river Ils.
- Water levels in diagram indicate downward flow in local flow system with fresh water and upward flow in the regional saline flow system.
- The occurrence of salt water is coincidental. in the sense that a very similar flow pattern would emerge with fresh water only. For explanations, see the next slide.

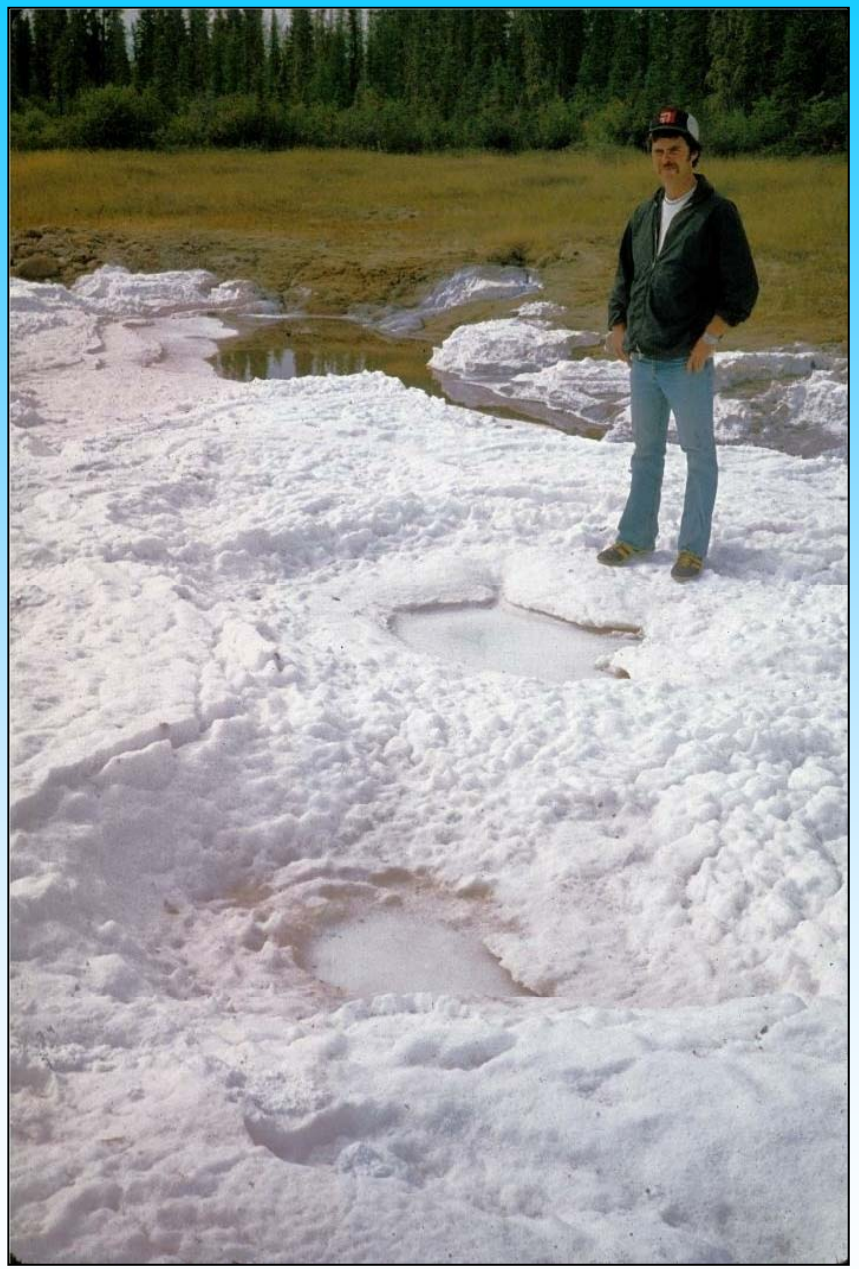
[Gronemeier et al, 1990, Fig.7]



after Weyer, 1996

Why is fresh water modeling suited to determine the flow lines of saline seawater?

- Freshwater determines the field of the potential in the subsurface (see slide 17).
- With a density of 1.03 g/cm^3, the vectoral pressure potential force [(grad p)/ρ_s] for this ocean-type saline water is very similar in magnitude to that of fresh groundwater with a density of 1.00 g/cm^3 and has the same direction.
- Thus, the flow directions are very similar for ocean-type saline groundwater and fresh groundwater.
- This has been verified by the occurrence of saline water at a depth of about 50 m below ground in borehole 226 and in the model results (see slide 37).



picture: K.U.Weyer, 1977

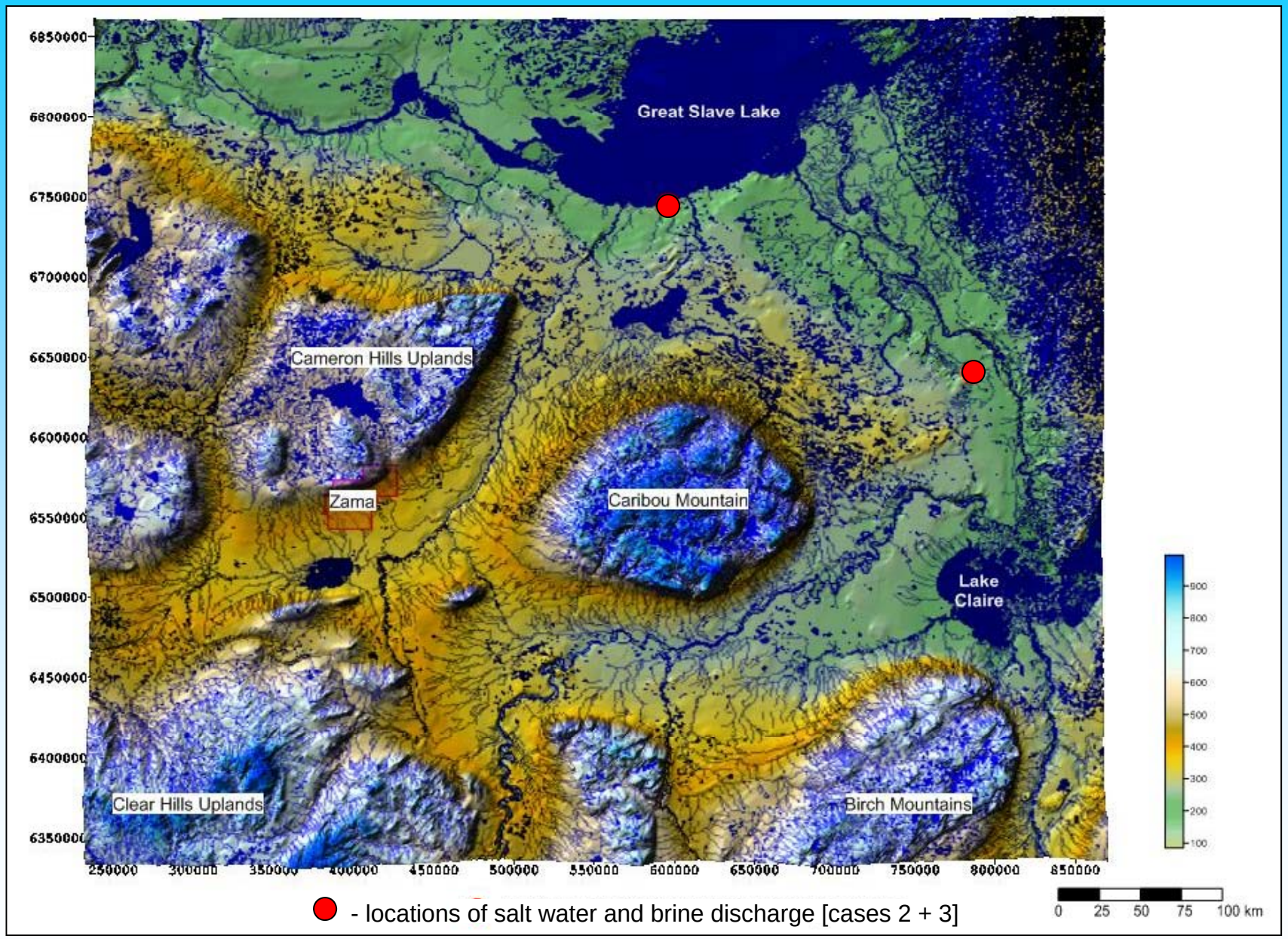
Case 2: Upward discharge of saturated brine near Salt River, NWT, Canada

- Saturated [~350 g/l; density ~1.3 g/cm^3] brine discharging upwards beside a creek
- Salt deposit is caused by precipitation of salt not by evaporation of brine.

Case 3:
Southern shore of Great Slave Lake, NWT, Canada

picture: K.U.Weyer, 1977

Open borehole discharging saline water



Crystal Geyser, Green River, Utah

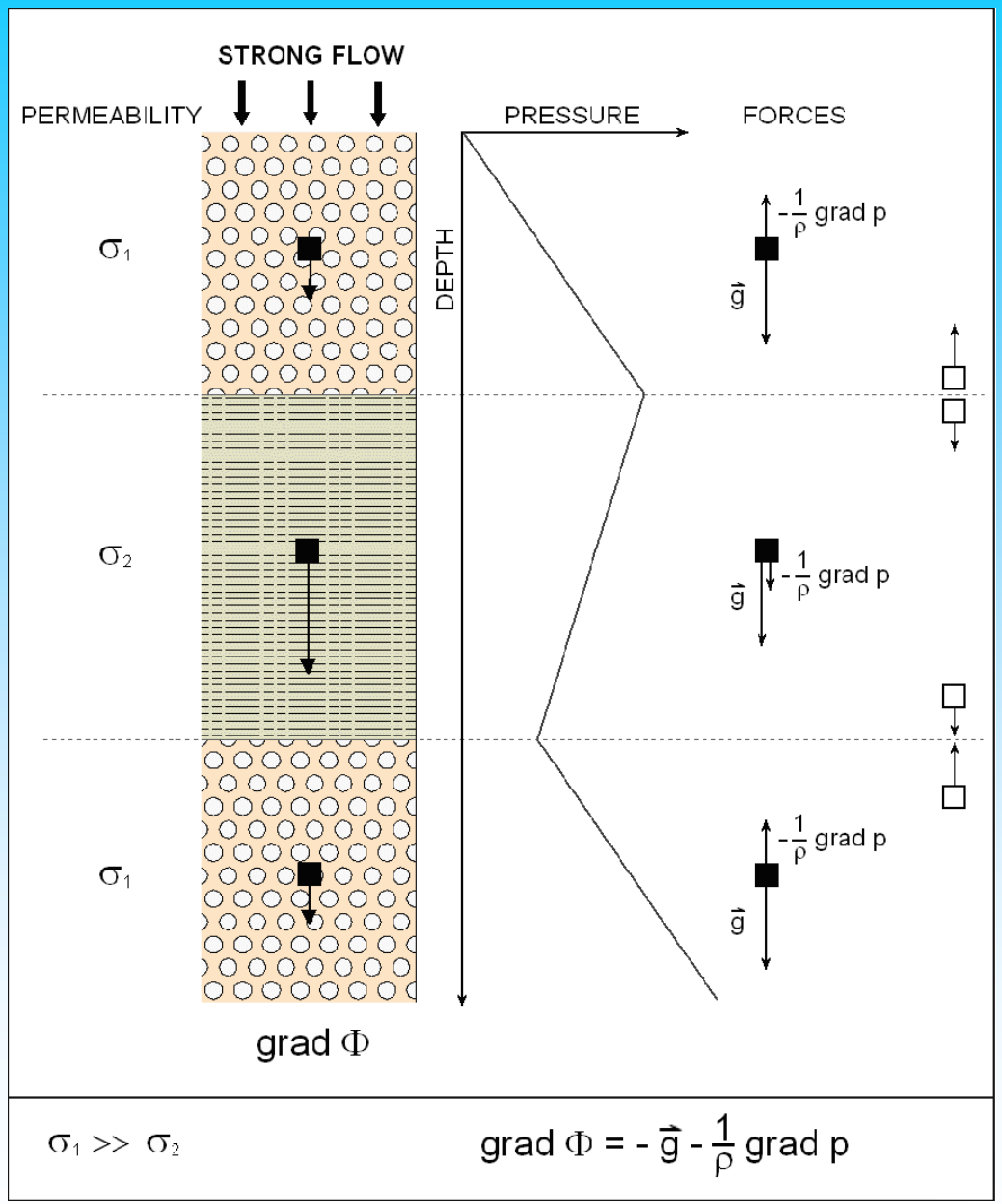
Field example of natural discharge of CO_2 by deep seated regional groundwater flow systems

Crystal Geyser on the bank of the Green River, Utah

Crystal Geyser erupting

Demonstration of deep groundwater flow with dissolved CO_2 entering a surface water body from underneath.

Downward-Directed Pressure Potential Forces: ‘Buoyancy Reversal’



Directions of gravitational and pressure potential forces at 'Buoyancy Reversal'

grad Φ = hydraulic force

$-\vec{g}$ = gravitational force

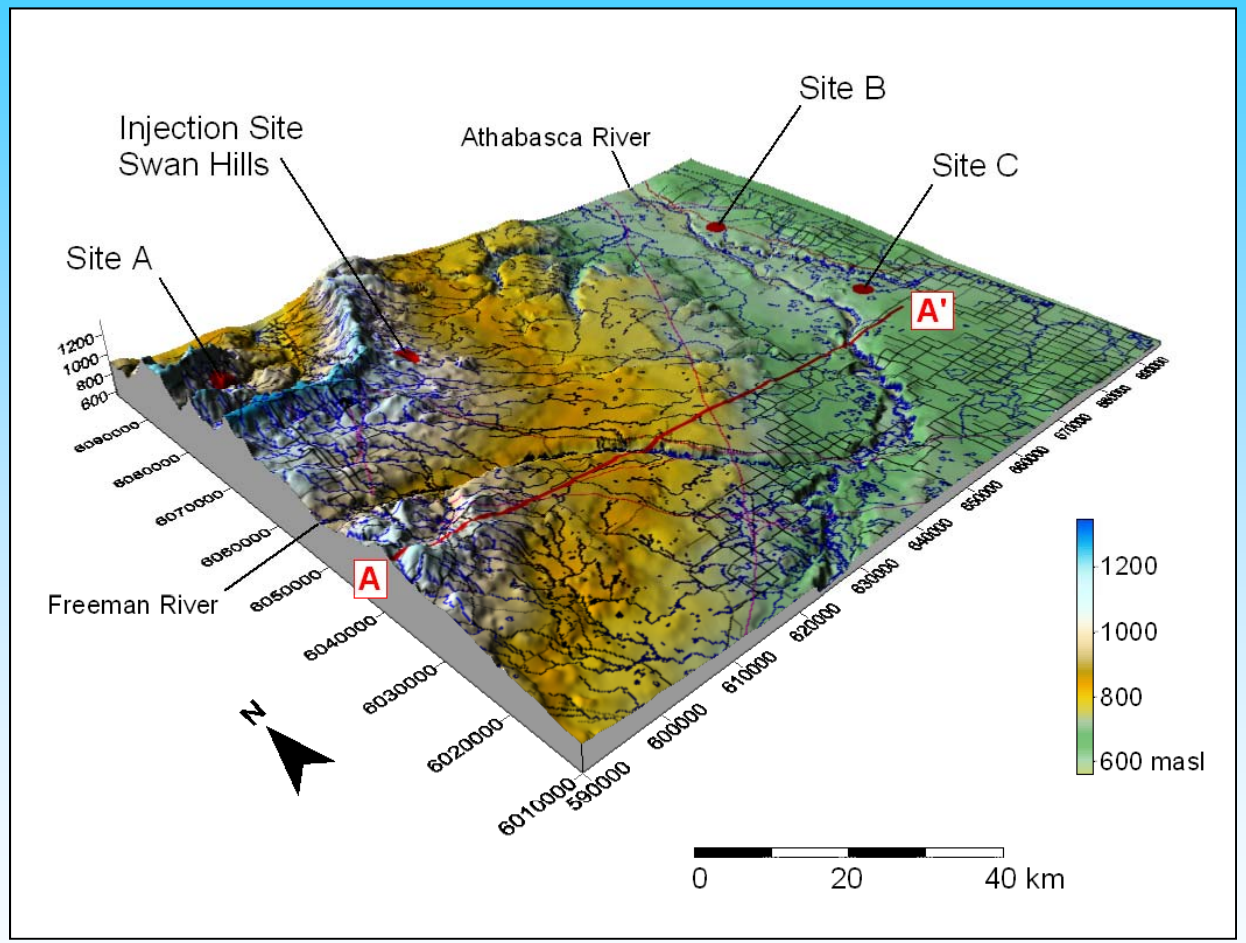
$-\frac{1}{\rho}$ grad p = pressure potential force

Modified after Weyer, 1978

K. U. Weyer, 20060208

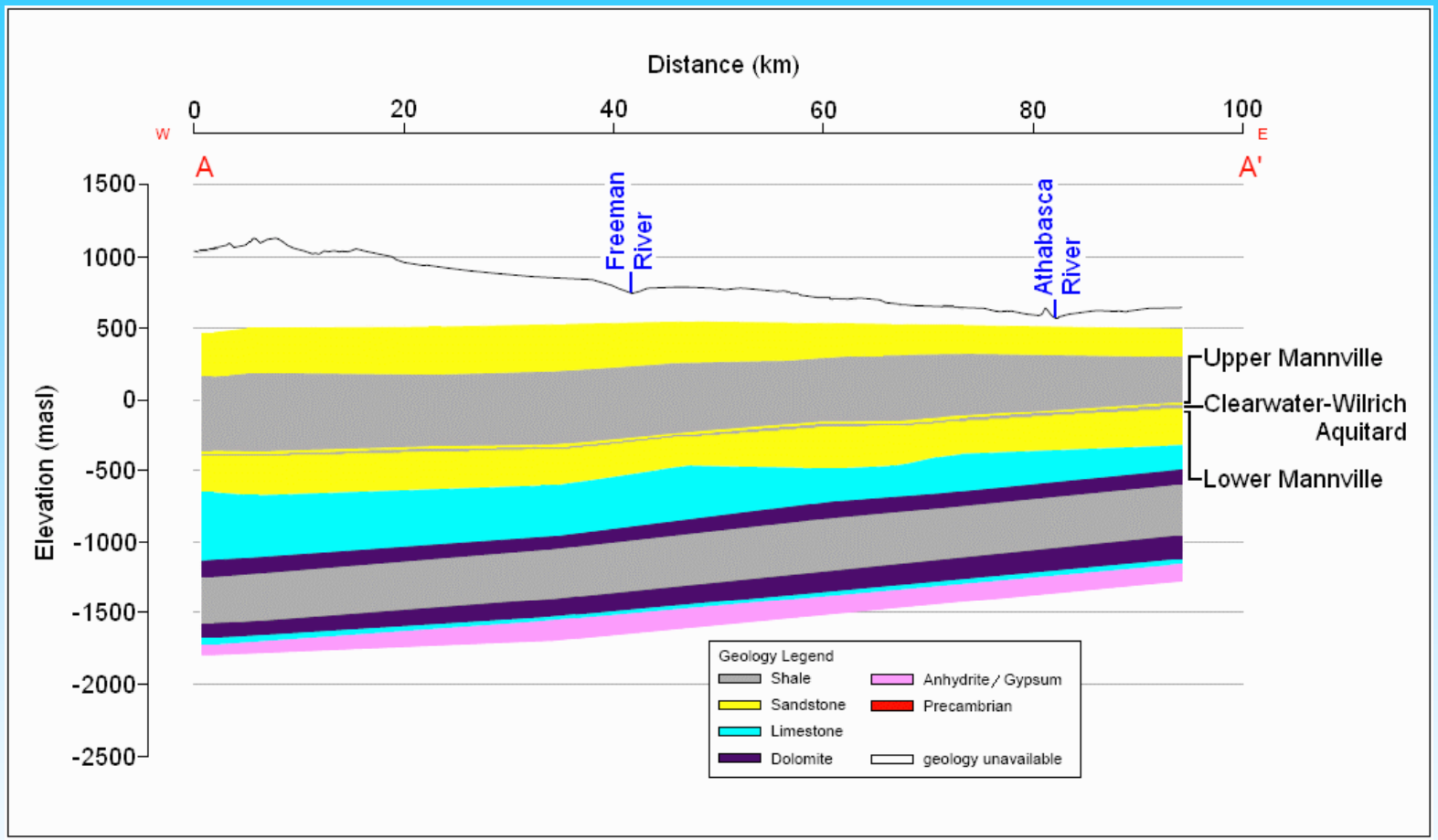
Field example: Swan Hills area, Alberta

Digital Elevation Model [DEM] of the Swan Hills area, Alberta, one of the places where 'Buoyancy Reversal' was measured in the field



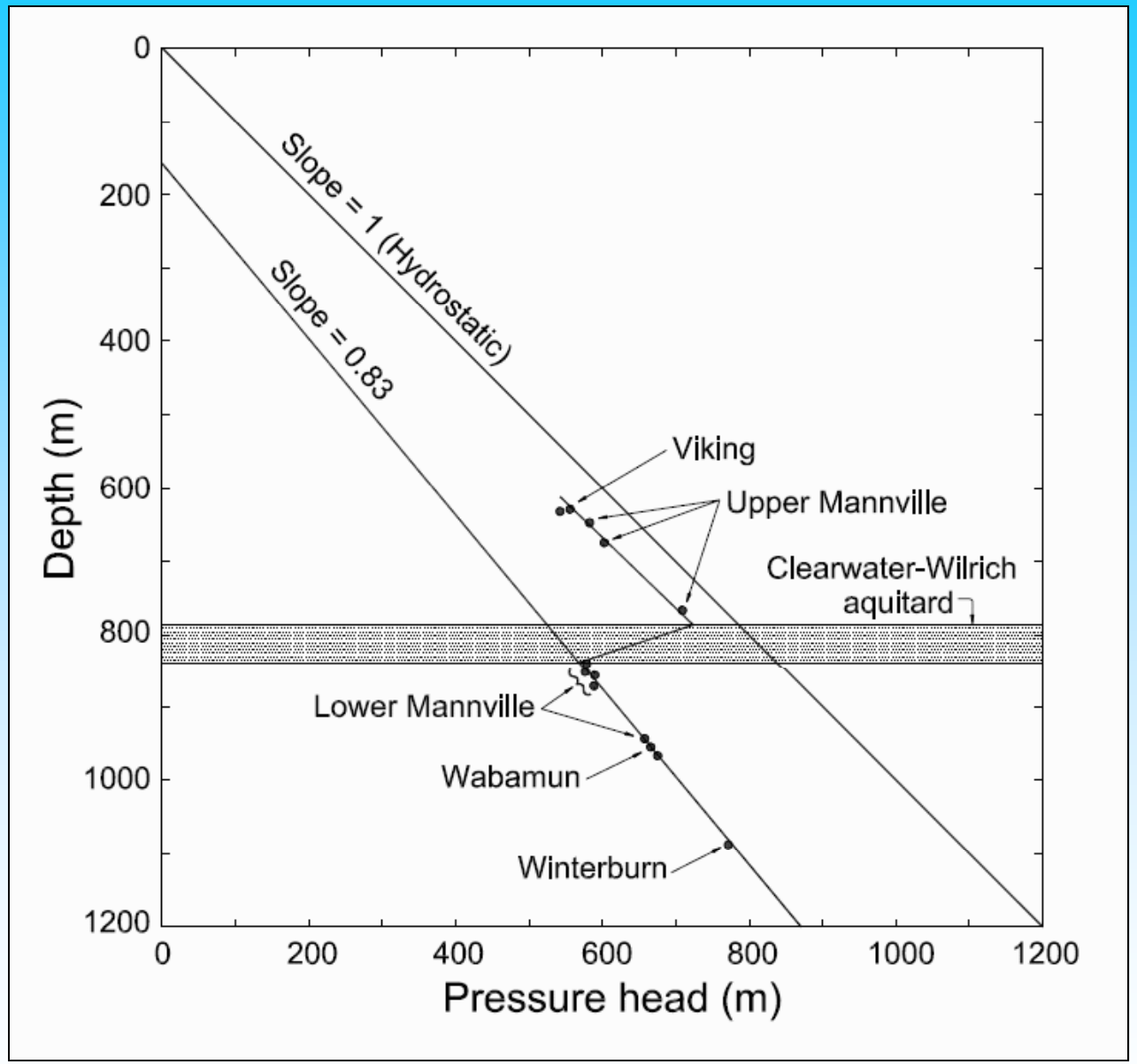
The geologic cross-section A-A' is marked as a red line. At the sites A,B, and C the occurrence of 'Buoyancy Reversal' was determined to occur within the Clearwater-Wilrich aquitard.

Geologic cross-section A-A'.



Substantial limestone and dolomite aquifers occur beneath the Clearwater-Wilrich Aquitard [the layer with field-measured 'Buoyancy Reversal']. The regional groundwater flow systems penetrate through the Clearwater-Wilrich Aquitard into deeper aquifers and, under natural conditions, move towards the regional discharge area, the Athabasca River valley.

‘Buoyancy Reversal’ at DEM Site A

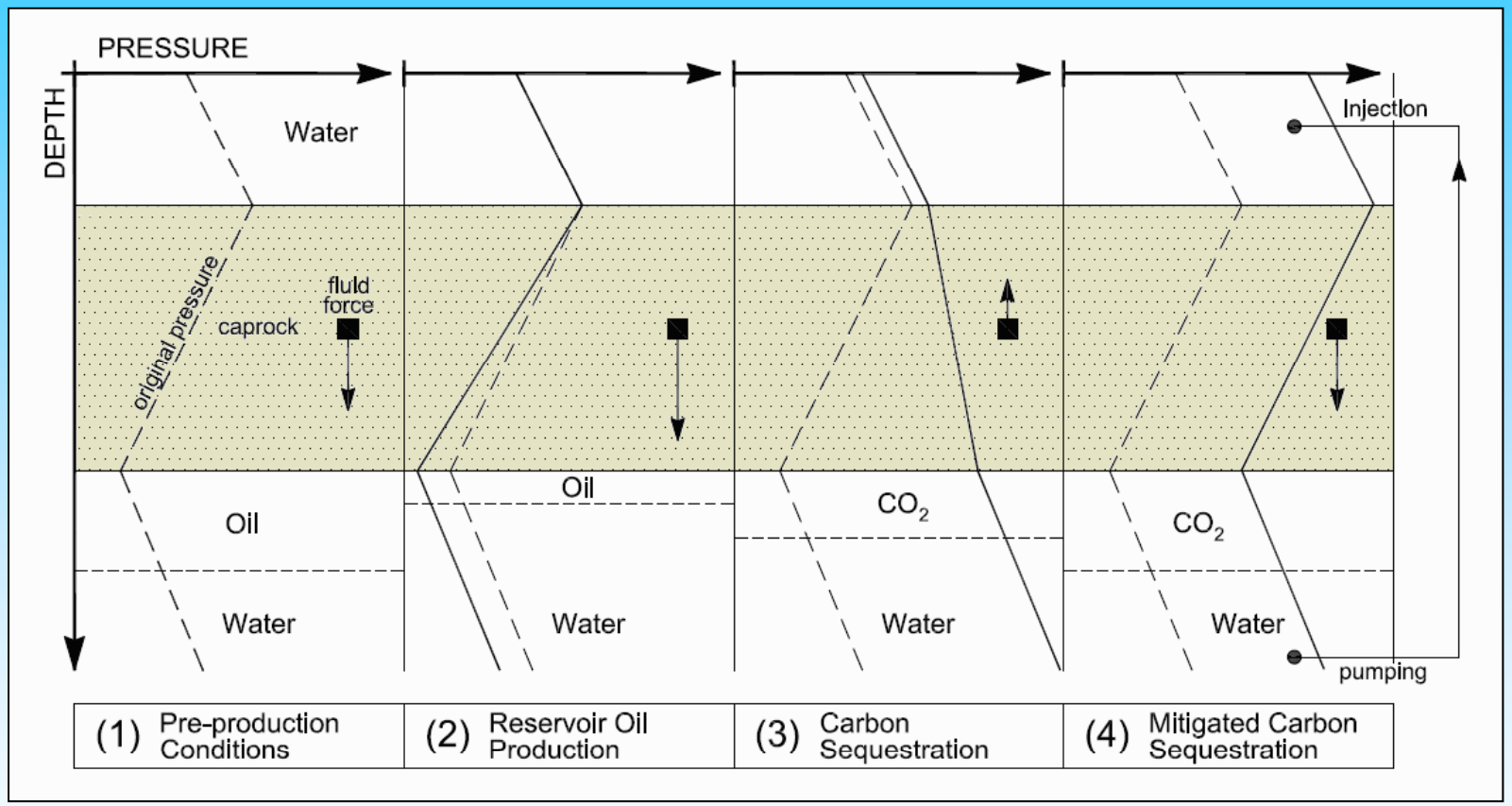


‘Buoyancy Reversal’ within the Clearwater-Wilrich Aquitard

Hitchon et al, 1989

Trapping of CO_2 under Conditions of 'Buoyancy Reversal' and its Maintenance

Trapping of CO_2 under conditions of 'Buoyancy Reversal'



Schematic pressure-depth relationship at (1) a natural occurrence of Buoyancy Reversal, and subsequent pressure pattern during (2) oil production, (3) carbon sequestration, and (4) mitigation of Buoyancy Reversal through pumping water from beneath the CO_2 layer (or other sources) and injecting it above the caprock

Conclusion

Subsurface fresh water force fields determine the flow direction for fresh water, salt water, oil, gas, and CO_2. Therefore, knowledge of gravitational systems of groundwater flow is imperative for understanding the long-term movement of oil, gas, and CO_2 in the subsurface as well as the monitoring and maintenance of injected CO_2 .

THE END

K. Udo Weyer, weyer@wda-consultants.com