Canada's Energy Geoscientists

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Dynamics of the Flow of Groundwater, Hydrocarbons, and Sequestered CO_2: Physics and Field Examples

by

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Notes of a course in conjunction with CSPG GeoConvention 2014
May 21-22, 2014 Calgary, Alberta, Canada

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01. Introduction and Overview

May 21-22, 2014 - Calgary, Alberta, Canada

Establishing Dr. Weyer's Credibility and Experience

Membership in the following scientific organizations:

- IAH - International Association of Hydrogeologists
- AIH - American Institute of Hydrology
- NGWA - National Ground Water Association [USA]
- AAPG - American Association of Petroleum Geologists
- AGU - American Geophysical Union
- CSPG - Canadian Society of Petroleum Geologists
- SPE - Society of Petroleum Engineers [USA]
- EAGE - European Association of Geoscientists and Engineers
- IMWA - International Mine Water Association

Dr. Weyer

- since 2008, has presented 86 times on the dynamic of groundwater flow as well as its effect on the migration of sequestered CO_2 in 16 countries on 5 continents before oil and other companies, governmental organisations, universities, workshops and conferences
in
Australia, Austria, Brazil, Canada, China,
France, Germany, Hungary, Italy, Iran, Japan,
the Netherlands, Poland, Portugal, UK, and USA

- proposed and co-organized an AAPG workshop on fluid dynamics [physics] of CO_2 sequestration. Gave a keynote address at this workshop.

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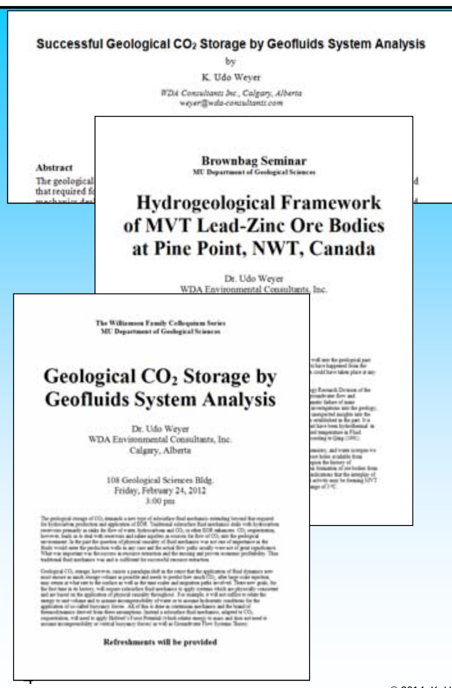
Successful Geological CO_2 Storage by Geofluids System Analysis
by
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Abstract

Brownbag Seminar
MU Department of Geological Sciences

Hydrogeological Framework of MVT Lead-Zinc Ore Bodies at Pine Point, NWT, Canada

Dr. Udo Weyer
WDA Environmental Consultants, Inc.

The Williamson Family Colloquium Series
MU Department of Geological Sciences

Geological CO_2 Storage by Geofluids System Analysis

Dr. Udo Weyer
WDA Environmental Consultants, Inc.
Calgary, Alberta

108 Geological Sciences Bldg.
Friday, February 24, 2012
3:00 pm

Refreshments will be provided

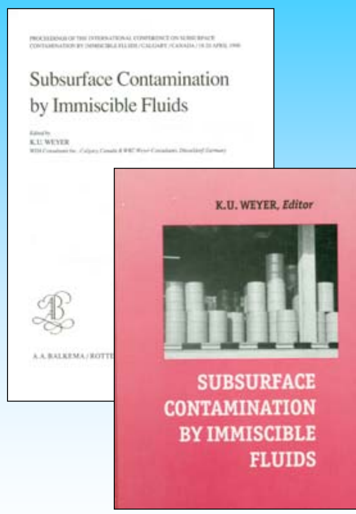
"Thanks for the very interesting presentation yesterday. We all learned a lot!."

Rob Bioletti, Technical Manager,
Regulatory Assessment, Carbon Capture and Storage Development
Alberta Energy, Dec 23rd, 2011

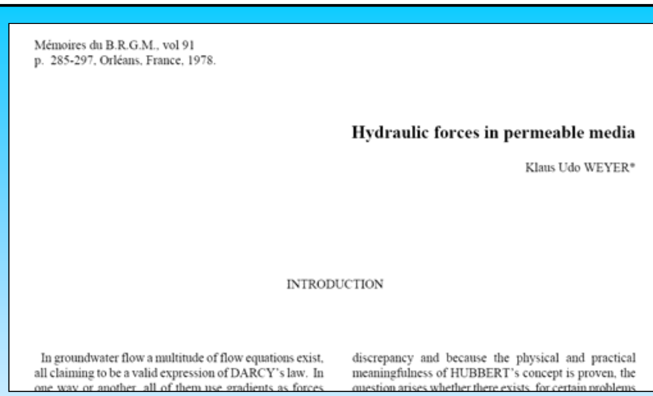
"It was good to have you visit. I enjoyed seeing you again and I think that your talks were good for our department."

Martin Appold, Professor [Hydrogeology, Economic Geology, Geochemistry]
Department of Geological Sciences
University of Missouri – Columbia
Feb 27th, 2012

Co-Chairman of the 1990 International Calgary IAH Conference "Subsurface Contamination by Immiscible Fluids" and editor of the 1992 Proceedings



The conference dealt with groundwater contaminants such as chlorinated and non-chlorinated hydrocarbons as well as other immiscible fluids.



Mémoires du B.R.G.M., vol 91
p. 285-297, Orléans, France, 1978.

Hydraulic forces in permeable media

Klaus Udo WEYER*

INTRODUCTION

In groundwater flow a multitude of flow equations exist, all claiming to be a valid expression of DARCY's law. In one way or another all of them use gradients as forces

discrepancy and because the physical and practical meaningfulness of HUBBERT's concept is proven, the question arises whether there exists, for certain problems

"Outside of the Soviet Union in which country most of applied hydrogeology and theoretical development takes place, Canada is foremost in its theoreticians Toth, Freeze and Weyer."

Peter Moore
"A Handbook of Hydrogeology"
Shell Canada Resources Ltd., internal handbook
January, 1981

Course Overview

Common misconceptions in the treatment of subsurface fluid flow

- Groundwater flows parallel to the water table and always in the direction of its slope
- 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 of the artesian aquifer
- Underground buoyancy forces are generally directed vertically upwards or downwards

A basic obstacle to scientific progress

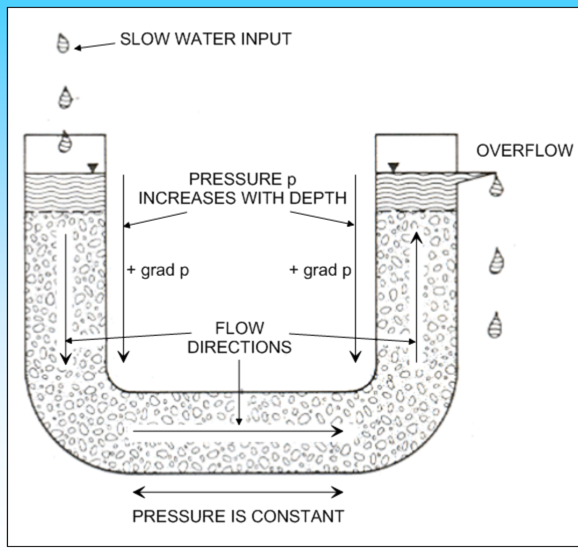
A scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die and a new generation grows up that is familiar with it.

- Max Planck, Scientific Autobiography

What drives subsurface fluid flow?

Pressure gradients?

Pressure is NOT the motor driving the motion of fluids in the subsurface



Water flows with and against the pressure gradient

after Weyer, 1978

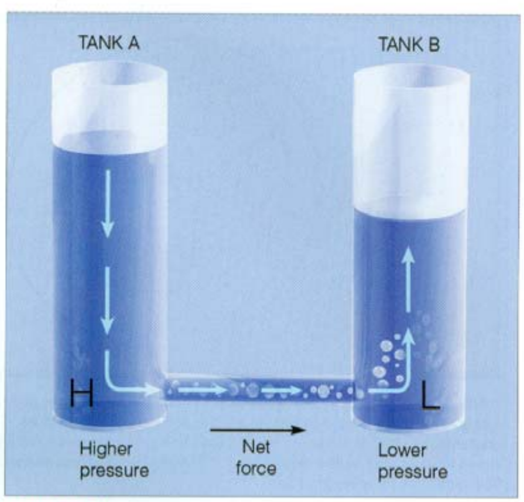


FIGURE 8.17 The higher water level creates higher fluid pressure at the bottom of tank A and a net force directed toward the lower fluid pressure at the bottom of tank B. This net force causes water to move from higher pressure toward lower pressure.

An example of misguided "physical" explanations in meteorology. Meteorology routinely ignores gravitational forces although air has the mass of approximately 1.225 kg/m^3 [at sea level and 15°C]

Regrettably, other branches of science dealing with fluid flow within engineering and natural sciences often fall into the same trap, as reservoir engineering, oceanography, and so-called physical hydraulics

Ahrens, 2012, p. 211

The driving force is Gravitation !!

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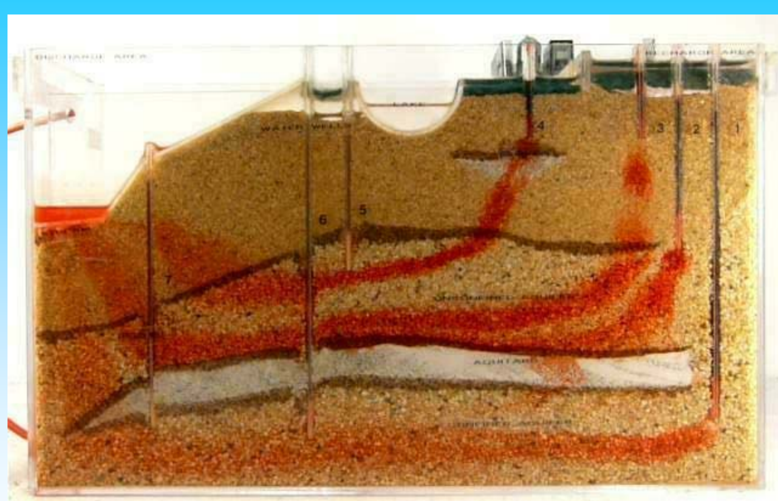

Demonstration of deep groundwater flow entering a surface water body from underneath.

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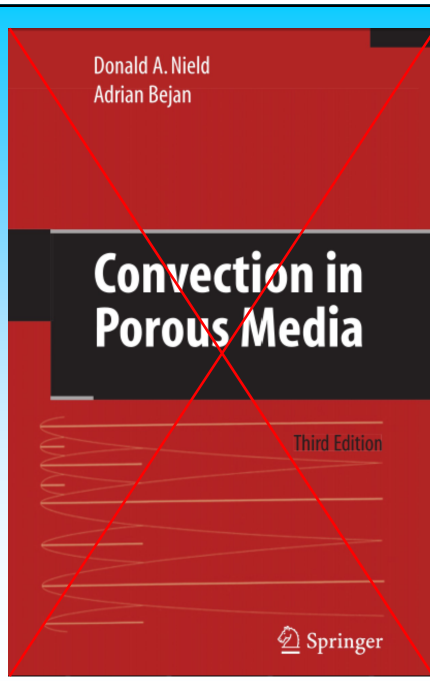

"Henry Darcy's (1856) investigations into the hydrology of the water supply of Dijon and his experiments on steady-state unidirectional flow in a uniform medium revealed a proportionality between flow rate and the applied pressure difference. In modern notation this is expressed, in refined form, by

$$u = -\frac{K}{\mu}\frac{\partial P}{\partial x} \qquad (1.2)$$

"Here $\partial P / \partial x$ is the pressure gradient in the flow direction […]"

Quoted from:

"Convection in Porous Media – Third Edition", by Donald A. Nield and Adrian Bejan, 2006, p.6.

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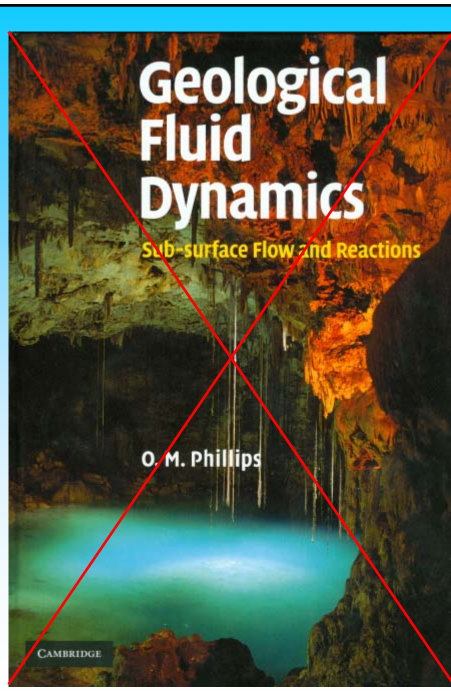

"Darcy knew a lot about hydraulics, he performed the experiment himself and he made the critical quantitative connection between flow rate and pressure gradient."

Quoted from:

"Geological Fluid Dynamics: Sub-surface Flow and Reactions", by O.M. Phillips, 2009, p.2

Compressibility of fluids

Many proponents of mathematical engineering hydraulics claim that water and oil are incompressible. That claim is one of the pillars of the mathematical engineering hydraulics.

As we have seen, both fluids are, however, compressible and thereby able to store energy necessary for upward flow in gravitationally driven flow systems. Energy gained by downward flow within the gravitational field is stored by compression of the unit mass of fluids. It is not stored by transfer into heat according to the second law of thermodynamics as is often assumed within mathematical engineering hydraulics.

Compressibility of fluids is one of the fundamental pillars of force potentials.

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(1) Pressure gradients are out as driving forces

Then, what drives hydrodynamic subsurface fluid flow?

(2) Velocity potentials?
(3) Force potentials? or
(4) density differences
of free convection?

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Which potential is it, velocity or force potential ?

Potential is a scalar quantity (as for example energy/mass) in a field with irrotational properties. For the two potentials above their gradients would be vectors denoting velocities or forces respectively.

Velocity potential is derived in the mathematical classical hydrodynamics of surface water in analogy to electrostatics (Lamb, 1879). Its derivative is a velocity.

Force potential has been derived by Hubbert (1940) by transferring Ohms Law for electricity to groundwater hydraulics. Its derivative is a force.

The request for **irrotational flow behaviour** has been formulated in mathematical engineering hydraulics for flow of ideal fluids. We will see in section 09 that within the subsurface, the friction behaviour of viscous fluids is such that, within un-researched limits, rotational variable density flow of salt water along a flow line can be adequately described by making use of force potentials.

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Velocity Potential [L^2T^{-1}]

for idealized incompressible frictionless fluids of classical hydrodynamics [Lamb, 1879]

Muskat (1937):

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

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

p. 71, claims to be Darcy's equation

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

p. 258, a velocity potential

Dachler (1936) :

$$q_x = -K \cdot \frac{\partial h}{\partial x} = -\frac{\partial (Kh)}{\partial x}$$

Bear (1972, p.122):

$$\mathbf{q} = K\mathbf{J} = -K\,\mathrm{grad}\,\varphi$$

de Marsily (1986, p.59):

$$\mathbf{U} = -\frac{k}{\mu}(\mathbf{grad}\,p + \rho g\,\mathbf{grad}\,z)$$

de Marsily (1986, p.52, 60) clearly states that his treatise will not use Hubbert's (1940) formulations for compressible fluids. Neither did Bear (1972).

Force Potential [L^2T^{-2}]

Compressible fluids

Potential Φ = energy / unit mass

Hubbert (1940)

$$\Phi = gz + \frac{p}{\rho}$$

fluid potential = gravitational potential + pressure potential

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

fluid force = gravitational force − pressure potential force

Head $h = z + P/\rho g$

Potential $\Phi = gh$

Comparison of equations of velocity potential with those of force potential.

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Scheidegger (1974, p. 79) states unequivocally:

"It is thus a force potential and not a velocity potential which governs flow through porous media"

(emphasis added)

Adrian E. Scheidegger. 1974. The physics of flow through permeable media. Third Edition. University of Toronto Press, 353 p.

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Davis and de Wiest (1966, p.169) explain in their textbook "Hydrogeology" (very popular at the time), the difference between velocity potential and force potential as follows:

"In ground-water flow, the products Kh *and* gh, *in which* K *and* g *are constants, are called* Φ *and* Φ^*, *and are respectively the velocity potential and force potential. The concept of force potential, developed by Hubbert [1940], is more general than the concept of velocity potential, which is strictly valid only for media with a constant* K, *characterized by a fluid of constant density and viscosity and by an intrinsic permeability which is constant in space. This is the case in most simplified hydrogeologic applications and the continued use of the velocity potential may be defended for this reason alone."*

Regrettably, knowledge and application of force potential has been fallen out of fashion within the last 50 years, possibly promoted due to the ease of data processing and computer application within mathematical engineering hydraulics. Davis and de Wiest's simple hydrogeological cases and applications do not exist anymore.

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Now let's turn towards the application of force potentials to the flow of fluids in the subsurface

In the 1960s and 1970s Hubbert's work on force potential was widely accepted as the physically correct way to deal with subsurface flow of fluids. Since then work with the competing velocity potential has again achieved wide acceptance in mathematical engineering hydraulics and problem solving over the physically correct force potential.

The rising requirements of large scale CO_2 sequestration, waste water injection, and the application of newly developed methods for unconventional hydrocarbon production caused a paradigm shift which needs to be responded to by applying to problem solving Hubbert's force potential, groundwater flow systems theory and the new insights on buoyancy forces.

In response, this course is based on the physics of force potential and the consequences originating for regional groundwater flow, application of buoyancy forces, variable density flow, CO_2 sequestration, physics of hydrodynamic traps, hydrocarbon production from hydrodynamic fields, and unconventional hydrocarbon production.

Paradigm shift: = a change in basic assumptions within the ruling theory of science [Kuhn, 1970]

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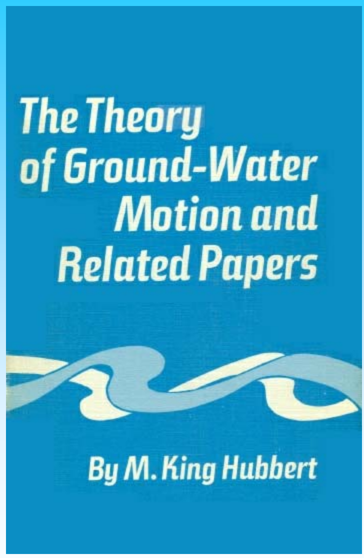

1969 – Introduction to Collection

1940 - The Theory of Ground-Water Motion

1953 - Entrapment of Petroleum Under Hydrodynamic Conditions

1956/57 - Darcy's Law and the Field Equations of the Flow of Underground Fluids

Online sources

Hubbert (1969):
not found online

Hubbert (1940):
http://www.jstor.org/stable/30057101

Hubbert (1953):
http://archives.datapages.com/data/bulletns/1953-56/data/pg/0037/0008/1950/1954.htm

Hubbert (1957):
https://www.onepetro.org/general/SPE-749-G

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Hydrostatic vs Hydrodynamic conditions

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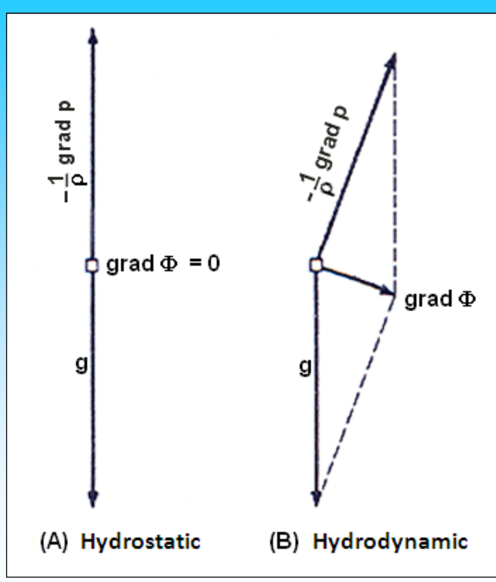

Hydraulic forces (grad Φ) under hydrostatic and hydrodynamic conditions

after Hubbert (1953).

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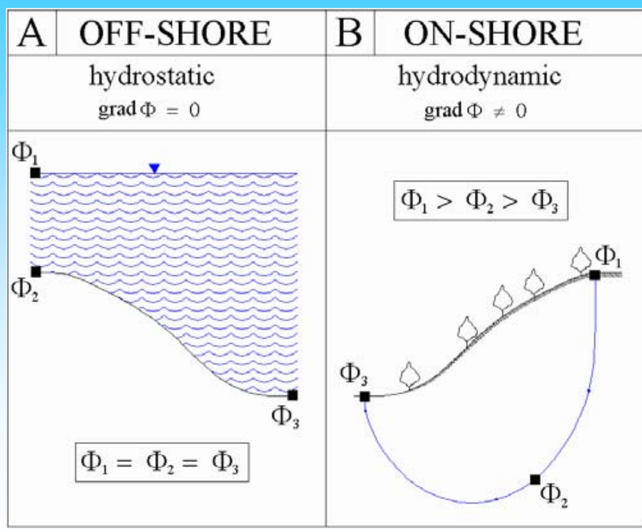
Comparison of hydrostatic and hydrodynamic conditions in subsurface fluid flow.



Φ : hydraulic potential
- grad Φ : hydraulic force

Weyer, 2010b

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Buoyancy and Buoyancy Reversal

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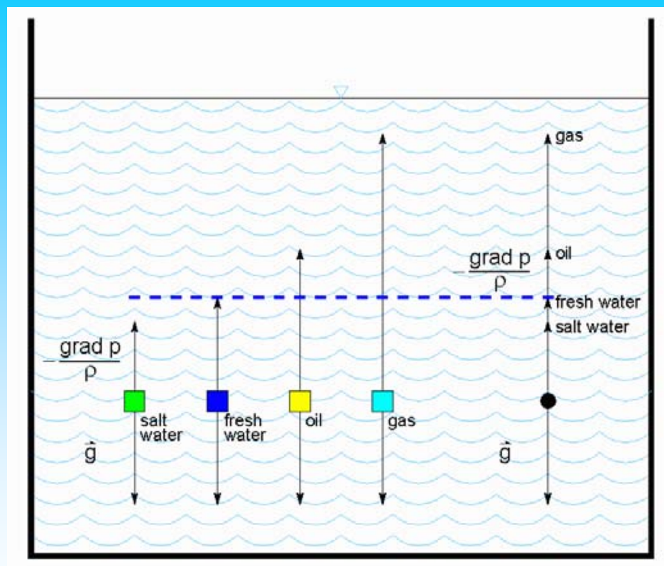

Hydrostatic buoyancy

after Weyer, 2010a

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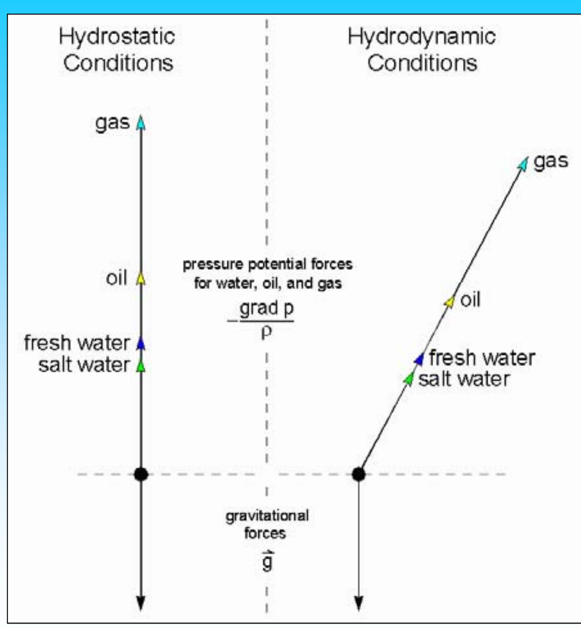

Comparison of force directions under hydrostatic and hydrodynamic conditions

after Weyer, 2010b

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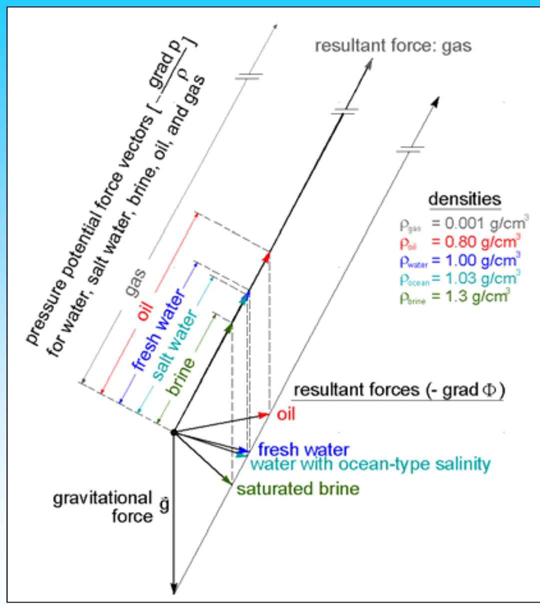

Hydrodynamic forces within the force field of fresh groundwater

after Hubbert, 1953

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Field example Salt River Basin, 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.

picture: K.U.Weyer, 1977

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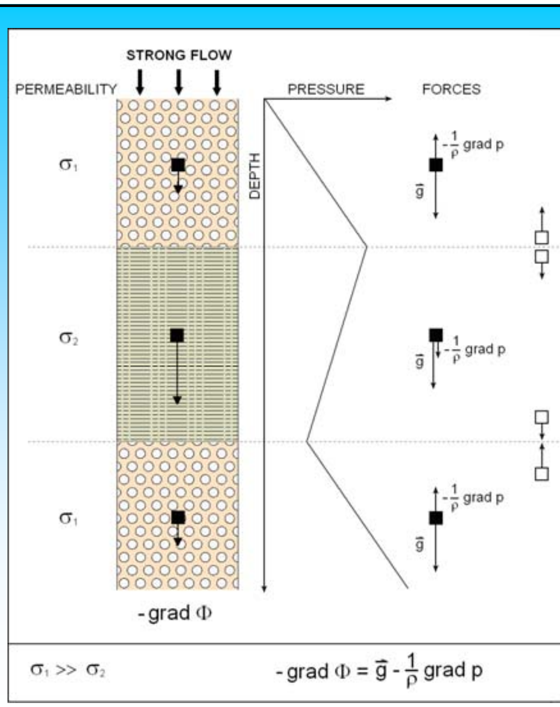

Buoyancy Reversal

in low-permeable layers under a recharge area with strong downward flow conditions.

Weyer, 2010a

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Variable Density Flow

- **Free convection:** water of higher density on top of a layer of less density forms downward directed fingers. – Under natural hydrostatic conditions in a lab or numerical model!
- **Convection cells?** - Under natural hydrostatic conditions!
- **Density changes** along flow lines by dissolution under natural hydrodynamic conditions

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Variable density
Variable density implies that the density varies in space.

Forced and Free convection (Bear, 1972, p. 642)
Convection imposed by internal means is known as forced convection, while fluid motion caused by density differences due to temperature variations in the field of flow is called free, or natural convection.

Advection is another expression for forced convection. The nomenclature is confusing. Under hydrodynamic conditions advection is in fact more natural than free convection.

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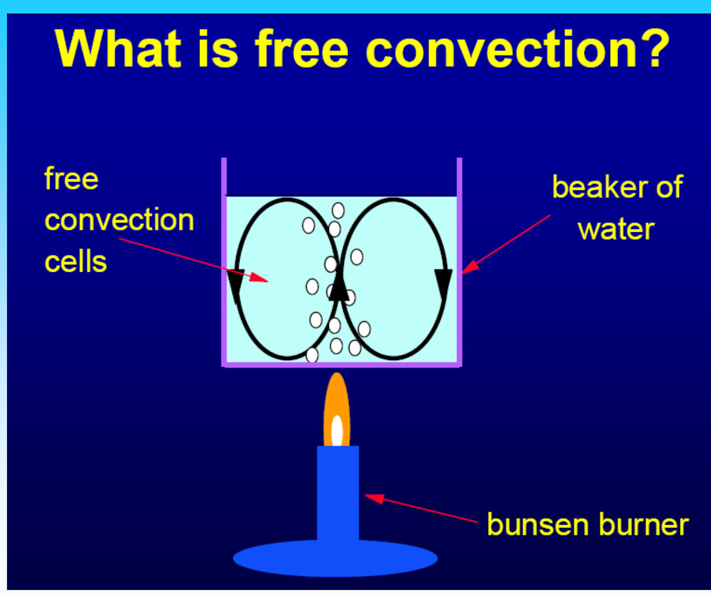

Simmons, 2011. Variable Density Groundwater Flow: From current challenges to future possibilities.

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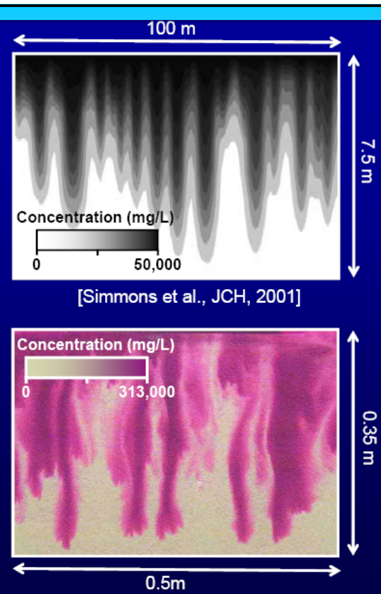


[Simmons et al., JCH, 2001]

[Simmons et al., TIPM, 2002]

Numerical modeling

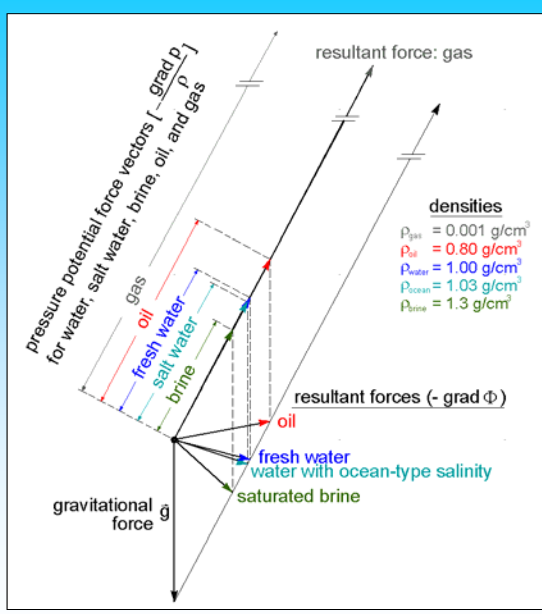
Hundreds of papers on theory, modelling & laboratory experiments on **finger instabilities** associated with free convection ….

BUT

A COMPLETE LACK OF CONCLUSIVE FIELD BASED EVIDENCE AND DATA !

Laboratory experiments

after Simmons, 2011



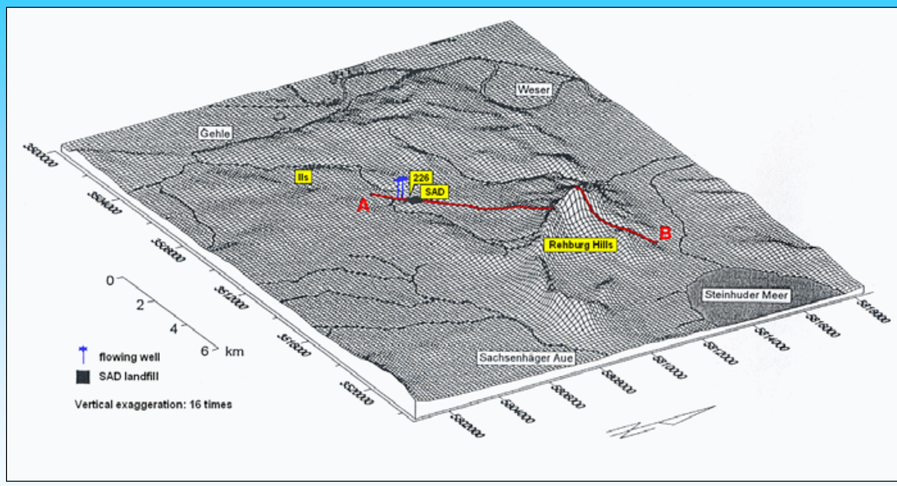
R E M E M B E R

Hydrodynamic conditions

Schematic diagram of variable density flow of fluid with differing densities within the fresh groundwater force field.

after Hubbert, 1953

Field study and numerical model with variable density along flow lines



after Weyer, 1996

Digital Elevation Model (DEM) of the Münchehagen landfill area, including position of cross-section A-B

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

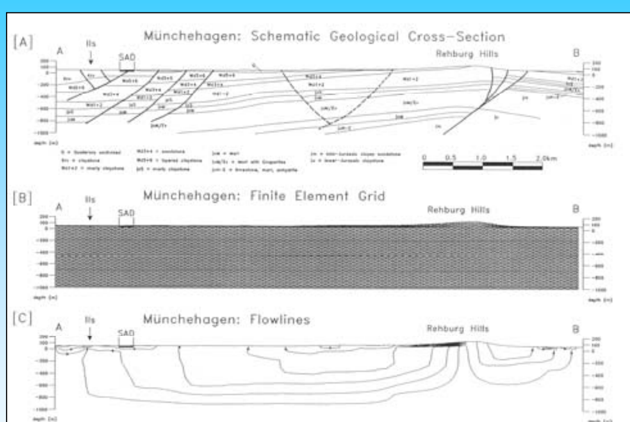
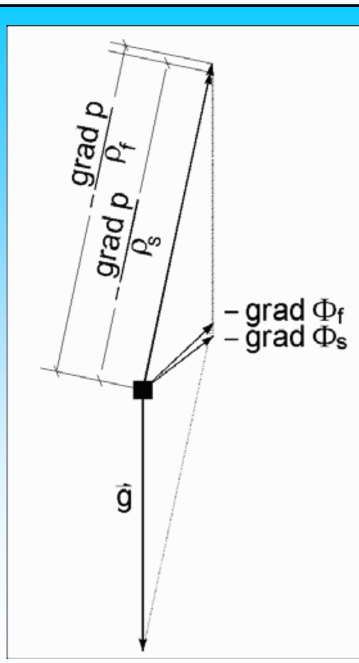


Fig. 3 A: Geological cross-section A-B (see Fig. 1). The geological profile was composed based on data from Jordan (1975) and Rohde (1992). B: Finite element grid for geological cross-section A-B. C: Vertical groundwater flow model Münchehagen: Flow lines in geological cross-section A-B. Vertical exaggeration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

Weyer, 1996

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



Why is fresh groundwater modeling suited to determine , within the geological framework, flow lines of groundwater with a salinity equal to that of seawater?

after Weyer, 1996

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Groundwater flow systems and role of aquitards

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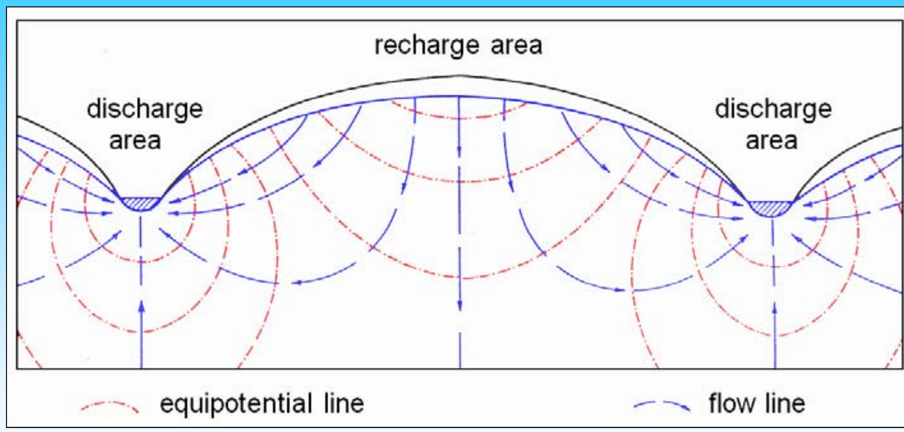

Groundwater flow pattern after Hubbert (1940), Figure 45.

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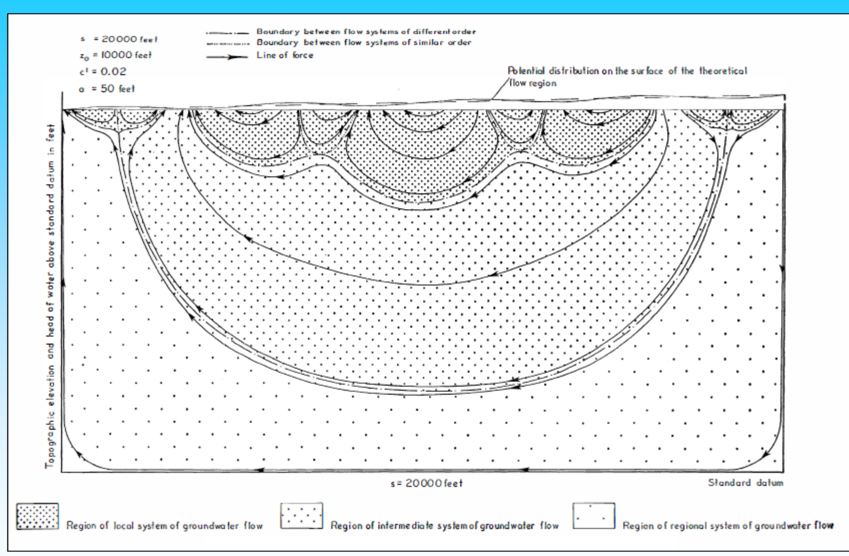

Mathematical model by Tóth [1963]: analytical calculation of groundwater flow systems in a cross-section with homogeneous and isotropic lithology

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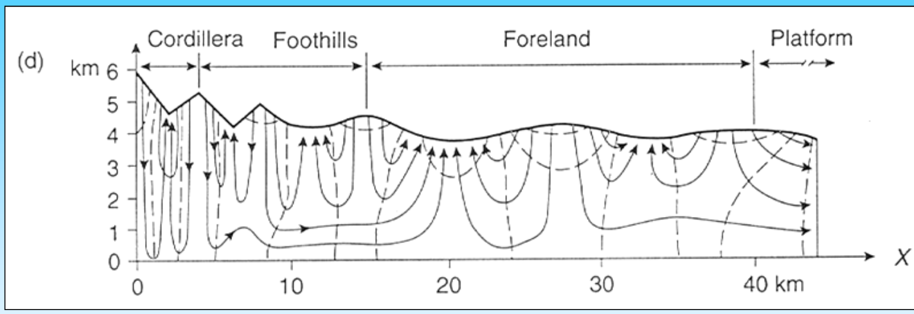

Tóth, 2009, Fig. 3.14

Gravitationally-driven groundwater flow can reach depths of 6 km or more.

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Erroneous assumptions about regional groundwater flow

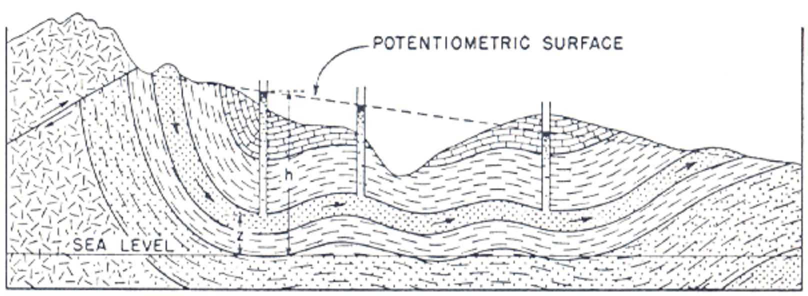

FIG. 11.—Regional flow of water through sand from higher to lower outcrop, showing continuous drop in potential.

Hubbert, 1953

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).

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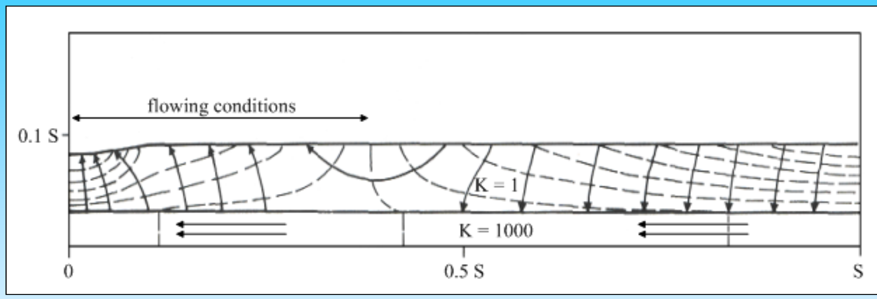
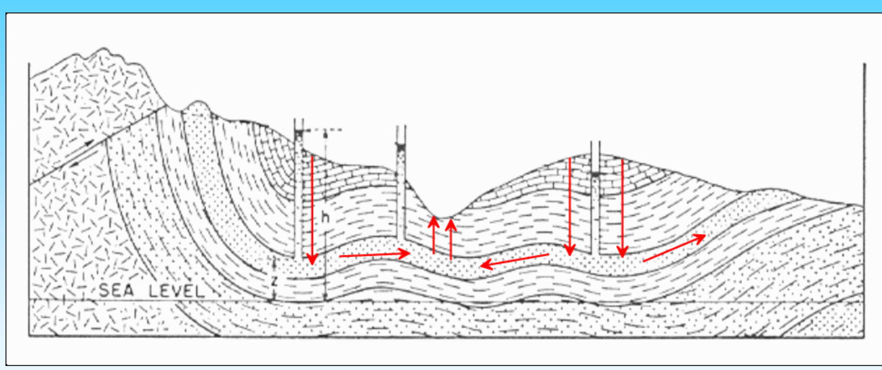
Role of aquitards within groundwater flow systems



After Freeze and Witherspoon, 1967, Figure 2C. Flow lines added.

Flow interaction between aquitard and underlying aquifer minimizes the total energy consumption. Under the above geometrical configuration twice as much groundwater flows through the aquitard as in the aquifer. Aquitards are integral and important parts of regional groundwater flow systems. For aqueous fluids they do not act as 'caprocks'!

Revised concept of regional groundwater flow



after Hubbert, 1953

Schematic representation.

Groundwater flow does not take the path of least resistance

instead

the multitude of pathways are arranged such that the energy consumption in the total flow field is minimized

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Following the theoretical portion of the course, a number of short case histories will be presented reporting field investigations and their interpretation with or without numerical modelling

Contained in Section 14:

- Blackie, Alberta
- Provost, Alberta
- Vermillion River, Alberta
- Numerical karst model, Athabasca Oil Sands
- Dorsten, Germany
- Bielefeld / Senne, Germany

Contained in other Sections:

- Yellowstone, USA: Section 08
- Münchehagen, Germany: Section 09
- Sand model: Section 13
- Brake, Germany: Section 13

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Synopsis

Section 1 provided an overview and short introductions of some of the major topics addressed within the following 17 Sections of the course notes. Many of the slides shown will also be incorporated within the more detailed sections below.