



Applying Hydrogeological Methods and Hubbert's Force Potential to Carbon Storage: A Primer

by

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

Part 1: Introduction and Explanations

Foreword	2
Summary	2
Key Points	4
Arrangement of Slideshow	9
Section Highlights	11
Conclusions	17
Credits	19
List of References	21

Part 2: Slides [two per page]

June 24, 2009
with corrections April 10, 2010, and Nov 27, 2014
© 2009 K.U.Weyer

Foreword

WDA's involvement in Carbon Sequestration started in August, 2008 when Dr. Weyer got an invitation by the Brazilian oil company Petrobras to present on the application of physics-based groundwater dynamics to carbon storage at a Salvador Seminar. It did not take long to find that the physics-based approach is an essential addition to methods applied so far to carbon storage. The physics-based methods of this primer will significantly increase the probability of avoiding unpleasant surprises that might come along if only reservoir engineering methods were used in the grand scale that worldwide carbon sequestration requires. All quoted papers on physical matters have been peer-reviewed within journals or under a review contract (as was the case with the paper Weyer, 1978).

When delivering a Powerpoint presentation at the Geofluids seminar of the Canadian Society of Petroleum Geologists (CSPG) on December 1st, 2008 in Calgary, a lively and in-depth discussion ensued on the matter of 'buoyancy forces'. Several participants found it difficult to accept that under hydrodynamic conditions the so-called 'buoyancy forces' would diverge from the vertical direction.

It became clear that the matter of 'buoyancy forces' constitutes a major stumbling block in accepting Hubbert's (1940, 1953, 1957, 1969) derivation of force potential and force fields. Because of this reason we decided to write highlights for all sections and additional explanations for the attached Powerpoint slideshow. Additional slides were added to the buoyancy subsection to shed light on the dependence of the so-called 'buoyancy forces' upon pressure potential forces under both hydrodynamic and hydrostatic conditions. In fact, it is the case that the directions of the fresh water pressure potential gradients determine the direction of the so-called 'buoyancy forces' under both hydrostatic and hydrodynamic conditions. It so happens that the pressure potential forces are directed vertically-upward under hydrostatic conditions, but may take any direction in space under hydrodynamic conditions.

The written text and the slideshow have been divided into sections by topics, and thus provide a guide for the reader to study the topics of particular interest. We recommend, however, that the reader follow the logical sequence of all topics.

Summary

The long term fate and leakage of CO₂ injected into geological formations depends as much upon Hubbert's mechanical Force Potentials for fluid flow in the subsurface (Hubbert, 1940) as upon the geologic structures. These force fields of Hubbert's Force Potential [energy/unit mass] are created within fresh groundwater in response to gravitational energy omnipresent in the subsurface. Forces within other fluids, such as salt water, oil, gas, and CO₂, are derived from the energy field of the fresh groundwater. Hubbert's force fields were applied in developing the Theory of Groundwater Flow Systems (Tóth, 1962, 2009, Freeze and Witherspoon, 1966, 1967). These flow systems penetrate into similar depth ranges as the injection of CO₂.

In areas of regional downward flow, the groundwater flow systems may cause 'buoyancy reversal', a term created by Weyer (1978), in low-permeable layers (aquifers and

caprocks). 'Buoyancy reversal' means that under certain geologic and hydrodynamic conditions in the subsurface, the so-called 'buoyancy force' (i.e. the pressure potential force) is directed downwards. These conditions have frequently been encountered in Alberta, Canada and in other areas. In general, under hydrodynamic conditions in the subsurface, the so-called 'buoyancy force' may be directed in any direction in space. These directions are determined by the directions of the pressure potential forces in the Force Potential field of fresh groundwater. Only under hydrostatic conditions is the so-called 'buoyancy force' (i.e. the pressure potential force) always directed vertically upwards.

After Hubbert's (1940) Force Potential had been proven physically correct, its application within the petroleum industry was simplified to allow the continued application of velocity potential for fluid flow calculations by incorrectly relating the energy to the volume [energy/unit volume], not to the mass [energy/unit mass].

As a consequence, these simplifications led to such invalid assumptions as

- water to be incompressible,
- the fluid flow would be driven by pressure and follow the direction of the pressure gradients,
- the fluid flow would, for all practical purposes, be concentrated in aquifers and fault systems,
- seepage to the surface could only occur where aquifers or fault systems connect to the surface or to shallow groundwater systems, barring leakage through boreholes,
- the belief that fluids of densities $> 1 \text{ g/cm}^3$ would remain at greater depth within the geologic layers,
- the belief that hardly any fluid passes through aquitards, while in reality, under natural conditions, often twice as much fluid passes through the overlying aquitards as through the underlying aquifer, and
- the isolated occurrence of up-dip and down-dip flow of fluids isolated within deep aquifers; again, this concept does not conform to the physics of Hubbert's (1940) Force Potential and Tóth's (1962) Theory of Groundwater Flow Systems.

The application of the principles of Hubbert's Force Potential to carbon sequestration is fundamental in achieving realistic results in any modelling attempt. In this author's view, the IPCC's attempt (Intergovernmental Panel on Climate Change, 2005, Fig. 5.8) to determine a 1000 year buoyancy-driven migration of CO_2 is seriously flawed as it ignores gravitational and pressure potential forces occurring within regional groundwater force fields. Similarly, Fig 5.25 (ibid.) is too much an over-simplification for its concepts to be applied at any realistic site investigation. The additional application of Hubbert's Force Potential, Tóth's Groundwater Flow Systems, and of hydrogeological monitoring methods will significantly improve the predictability of the behaviour of sequestered CO_2 .

What is generally missing from the treatment of this topic is the consideration of deeply-penetrating regional groundwater flow systems and its consequences using the principals of Hubbert's Force Potential. These points of view are illustrated with examples from the literature, with field studies, and with the results of mathematical modelling. Any risk analysis on carbon sequestration and subsequent leakage needs to

consider fluid flow analysis based on the principles of Hubbert's Force Potential and Tóth's Theory of Groundwater Flow Systems. Any application of hydrostatic 'buoyancy forces' (i.e. vertical pressure potential forces) in a hydrodynamic environment is erroneous. The application of Muskat's (1937) velocity potential (slide 17) is also incorrect even if the second term attempts to include gravitational forces in an "awkward" (Payne et al., 2008, p.53) manner.

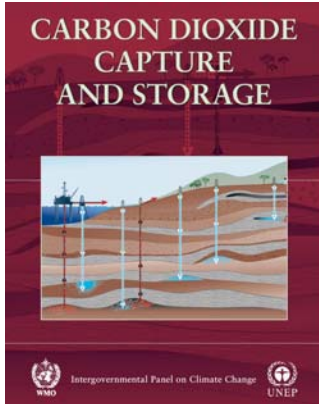
Key Points

For ease of orientation into the complex matters dealt with, the key points summarize key additions to the carbon storage methods applied so far in CCS. They are:

- Key Point 1: Limitations of the IPCC (2005) approach
- Key Point 2: Velocity Potential vs Force Potential
- Key Point 3: Regional gravitational flow of groundwater
- Key Point 4: Water penetrates caprocks
- Key Point 5: Regional permeabilities systemically exceed measurements in karstic and fractured rocks
- Key Point 6: Oil field pumping creates subsidence and fractures in caprocks and aquitards
- Key Point 7: Hydraulic windows depend upon contrasts of permeability, and are not limited to high permeabilities
- Key Point 8: Salt water moves upwards towards discharge areas
- Key Point 9: Omnipresent 'buoyancy forces' (i.e. vertical pressure potential forces) exist under hydrostatic conditions only
- Key Point 10: 'Buoyancy Reversal' may occur in aquitards and caprocks
- Key Point 11: Carbon monitoring also to be done using hydrogeological methods
- Key Point 12: Presently-available computer codes and simulators need re-writing for CO₂ storage.

Key point 1

[Section 3]



In IPCC (2005), carbon storage work has been dominated by the views of reservoir engineers and geophysicists.

It is necessary to incorporate modern hydrogeological views [role of fresh water force fields, deep- penetrating regional groundwater flow systems] into CCS as well.

Key point 2

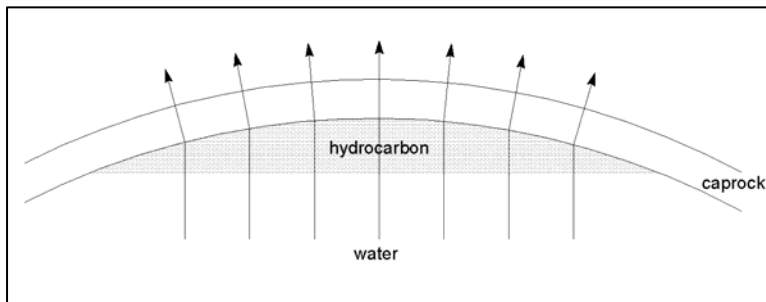
[Section 3, slide 15]

Velocity Potential	Force Potential
<ul style="list-style-type: none"> ◦ Oil Industry: Reservoir Engineering ◦ Source: Muskat, 1937 ◦ $p = \text{energy} / \text{unit volume} [ML^{-1}T^{-2}]$ ◦ hydraulic forces: grad p ◦ area considered: reservoir only 	<ul style="list-style-type: none"> ◦ Oil Industry: Exploration Geologists General: Hydrogeology ◦ Source: Hubbert, 1940, 1953, 1957, 1969 ◦ $\Phi = \text{energy} / \text{unit mass} [L^2T^{-2}]$ ◦ hydraulic forces: grad Φ ◦ area considered: all rocks from groundwater table to selected depth, including reservoir

Carbon sequestration needs to be dealt with using Hubbert's Force Potential.

Key point 3

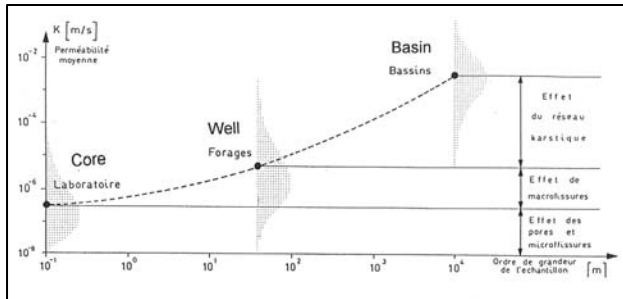
[Sections 4+10, slides 24, 113]



Caprocks [aquitards] are considered to be impermeable to hydrocarbons [due to capillary forces] but they are permeable to water flow in either normal direction.

Key point 4

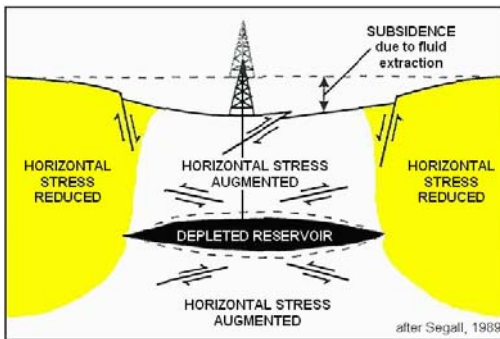
[Section 5, slide 34]



Regional permeabilities of fractured or karstic rocks are often 2 to 4 orders of magnitude larger than permeabilities measured in well tests.

Key point 5

[Section 5, slide 35]

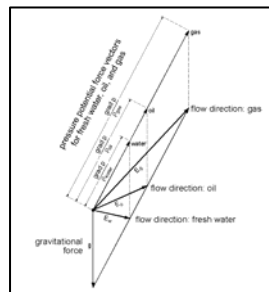
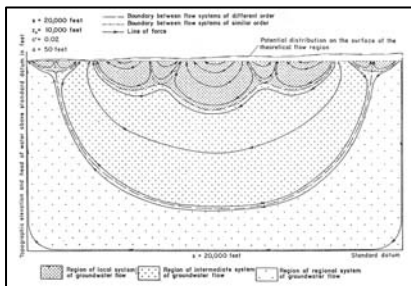


Pumping in oil or gas fields creates stress-induced fractures in caprocks and aquitards due to subsidence.

Injection of CO₂ will cause heave, thus rejuvenating previously-created subsidence-related fractures and possibly creating new ones

Key point 6

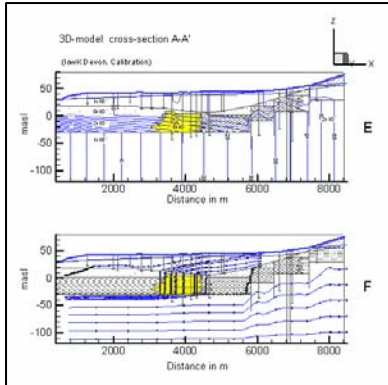
[Section 6, slides 58, 97]



Regional gravitational flow of groundwater creates the force fields determining the flow directions of hydrocarbons and CO₂ in the subsurface.

Key point 7

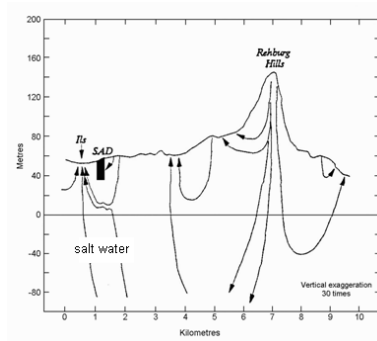
[Section 6, slide 78]



Hydraulic windows (here yellow) are determined by permeability contrasts, not by absolute permeability values.

Key point 8

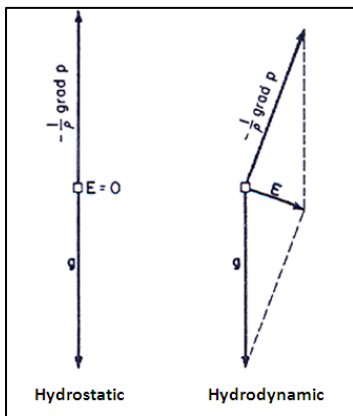
[Section 7, slide 85]



The flow directions for fluids with a density $> 1 \text{ g/cm}^3$ are determined by the fresh water potential field. Salt water moves toward discharge areas.

Key point 9

[Section 8, slide 96]

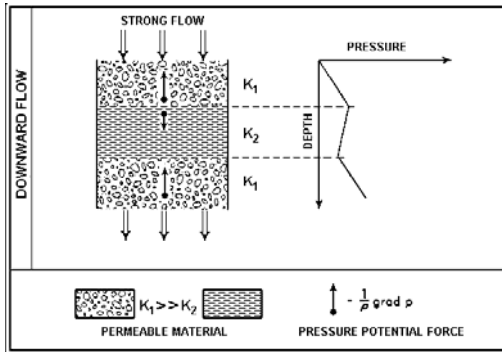


from Hubbert, 1953

Omnipresent 'buoyancy forces' (i.e. vertical pressure potential forces $[-1/\rho \text{ grad } p]$) exist only under hydrostatic conditions but not under the hydrodynamic conditions of the subsurface.

Key point 10

[Section 9, slide 100]

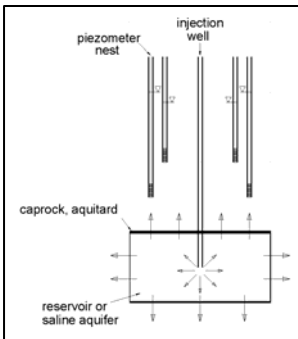


'Buoyancy Reversal'

The so-called 'buoyancy forces' (i.e. pressure potential forces $[-1/\rho \text{ grad } p]$) can be directed downwards in aquitards (caprocks) thus hindering the upward migration of hydrocarbons and CO_2 .

Key point 11

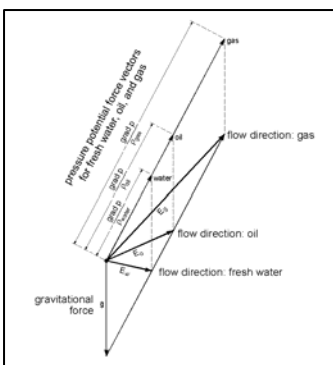
[Section 10, slide 114]



Monitoring systems for carbon storage applied to date concentrate mainly on geophysics, and have missed the hydraulic methods of hydrogeology.

Key point 12

[Section 10]



Due to widespread and erroneous assumption of 'buoyancy forces' (i.e. vertical pressure potential forces) and its incorporation in computer simulation codes, these codes need to be rewritten for CCS work to reflect the pressure potential forces in fresh groundwater force fields in determining the directions and migration times for CO_2 flow.

Arrangement of Slideshow

This list helps to locate any particular slide in the slideshow and allows the reader to choose a section that he would like to concentrate on.

<u>Section</u>	<u>Contents</u>	<u>Slide</u>
1	Paradigm shifts in subsurface flow	4
2	Common misconceptions in subsurface fluid flow	6
3	Why does groundwater flow?	7
	• Paradigm Shift: Darcy Equation	8
	• Laplace Equation	9
	• Paradigm Shift: Force Potential Φ	10
	• Velocity Potential Φ	17
4	Why do other fluids flow in the subsurface?	18
	• Role of fresh water force fields	19
	• Capillary forces	22
5	Measurement of hydrogeological properties	26
	• Hydraulic, gravitational and pressure potential heads	27
	• Piezometer nests	28
	• Permeability units and conversion	29
	• Range of permeabilities in various rocks	33
	• Permeability dependence on scale of measurements	34
	• Increase of permeability due to subsidence and heave	35
	• Porosity	36
6	How does groundwater flow?	37
	• Paradigm Shift: Hubbert, 1940: Force Potential	38
	• <i>Hubbert's theoretical approximation of groundwater flow between two valleys</i>	38
	• <i>Sand model of groundwater flow and 2D-vertical mathematical model [1]</i>	39
	• Counterplay of forces	40
	• Paradigm Shift: Tóth, 1962: Groundwater Flow Systems	56
	• <i>Field example: Turner Valley, Alberta</i>	57
	• <i>Mathematical model [2] by Tóth [1962]</i>	58
	• <i>Mathematical models [3] by Freeze and Witherspoon [1967]</i>	59
	• <i>Continuity of flow between aquitard and aquifer</i>	61
	• <i>Field example France: How to see groundwater flow systems penetrate aquitards</i>	63
	• <i>Erroneous assumptions about regional groundwater flow</i>	66
	• <i>Field example and 2D-vertical mathematical model [4]: Brake landfill in Germany</i>	69
	• Silt [10^{-8} m/s, 1 mD] as an efficient hydraulic window	75
	• <i>Field example and 3D-mathematical model [5]: Düsseldorf/Hilden, Germany</i>	75

<u>Section</u>	<u>Contents</u>	<u>Slide</u>
7	Upward-discharging salt water and brine	79
	<ul style="list-style-type: none"> • Field example and mathematical model [6]: Upward discharge from depth of 1000 m of ocean-type saline water at Münchehagen, Germany • Field example Salt River Basin, NWT, Canada: Upwards discharge of saturated brine • Field example Great Slave Lake, NWT, Canada: Upwards discharge of saline water 	80 88 89
8	Pressure potential forces versus 'buoyancy forces' (a misnomer).....	91
	<ul style="list-style-type: none"> • Pressure potential forces ('buoyancy') under hydrostatic conditions • Reason for change of magnitude of pressure potential forces of salt water, oil, gas, and CO₂ from that of fresh water • Comparison of pressure potential forces under hydrostatic and hydrodynamic conditions • Differing flow directions for fresh water, oil, and gas within the same fresh water force field 	92 94 95 97
9	Paradigm Shift Weyer, 1978: 'Buoyancy Reversal'	98
	<ul style="list-style-type: none"> • Theory • Field example: Swan Hills, Alberta 	99 102
10	Geological storage of CO ₂	110
	<ul style="list-style-type: none"> • Sink conditions versus source conditions • Mathematical models by IPCC [7] and Princeton [8] • Effect of deep wells upon fluid flow <ul style="list-style-type: none"> • <i>Microannuli</i> • <i>Deep well abandonment</i> • Field examples and mathematical models <ul style="list-style-type: none"> • <i>Field example and mathematical model [9]: Hayter field, Provost area, Alberta</i> • <i>Field example and mathematical model [10]: Freed investigation, TWP 50-51, Rge 14-15 W4M Alberta</i> 	111 115 118 122 126 128 128 132

Section Highlights

The section highlights help to convey the framework for the topics dealt with therein. It helps the reader to peruse the topics that are of particular interest.

1. Paradigm shifts in subsurface flow

Shows the essential improvements in dealing with subsurface flow, the 'new scientific truths'. Explains why these improvements are almost never accepted by contemporary scientists and practitioners.

2. Common misconceptions in subsurface fluid flow

Lists stumbling blocks delaying and preventing understanding of the physical processes governing fluid flow in the subsurface

3. Why does groundwater flow?

Explains the essential and basic equations dealing with groundwater flow and their proper use from the viewpoint of physics. The sole application of pressure gradients as driving forces is inadequate and leads to incorrect flow directions, volume and velocities, as does the application of velocity potentials under anisotropic and/or heterogeneous conditions..

4. Why do other fluids flow in the subsurface?

Fresh groundwater (density 1 g/cm^3) determines the energy field for all fluids in the subsurface. Therefore directions of pressure potential forces ($[-\text{grad } p]/\rho$) for all subsurface fluids follow the pressure potential force directions of the fresh water albeit their magnitude is different, either larger when the density $\rho < 1 \text{ g/cm}^3$ (oil, gas, CO_2) or smaller when that fluid's density $\rho > 1 \text{ g/cm}^3$ (salt water, brine).

Hence the pressure potential force directions of all fluids in the subsurface are dependent on the geometry of the pressure potential force fields of fresh groundwater. What is different are the flow directions of the individual fluids due to the effect of vectoral addition of the differing magnitudes of the pressure potential forces with the gravitational force g . These differences in resultant flow directions may be large (slides 21 and 97) or small (slide 87).

Capillary pressure potential forces are mechanical forces and are also taken into account by vectoral addition. Their direction and magnitude is, however, not determined by the geometry of pressure potential force fields of fresh groundwater but by the geology and the steepest rate of increase of the grain size of the sediment (Hubbert 1953, p.1977). The force will be pointing in the direction of this steepest increase of grain size change if preferentially water-wet or in the opposite direction if preferentially oil-wet or CO_2 -wet.

5. Measurement of hydrogeological properties

This section summarizes the determination, ranges and comparison of basic hydraulic properties such as heads, porosity, the various permeability units and their meaning, as well as the dependence of resulting permeabilities upon the scale of measurements (core, well tests, regional) and subsidence occurring during pumping of oil and gas fields. It turns out that it is nearly impossible to determine the actual

regional permeability of fractured or karstic rocks by direct measurement and that this regional permeability could be several orders of magnitude higher than the permeabilities measured in the field (slide 34). Slide 35 shows the principle of the creation of fractures due to subsidence. For the deep Dutch gas fields (pumping from about 3000 m depth from fractured rocks) a total surface subsidence of 1 m is expected to occur. The total movement in the immediate 'caprock' would be larger by an unknown amount leading to the formation of fractures related to stress changes. These fractures may be permeable to CO₂. Injection of CO₂ will cause heave and thereby rejuvenate subsidence-induced fractures and possibly create new ones. Formation of fractures will be indicated by micro-seismic events.

6. How does groundwater flow?

This section presents the various physical fields and their application in determining the flow pattern of fluids in the subsurface and is here divided into subsections.

Paradigm Shift Hubbert, 1940: Force Potential

First Hubbert's famous 1940 cross-section of groundwater flow between two valleys is shown and the concept of recharge and discharge areas is explained. Under hills, the flow is downward into the groundwater body (recharge area); under valleys, the flow is upward leaving the groundwater body into surface water bodies or evaporation (discharge area). Because of upward flow these discharge areas usually display artesian (flowing) conditions. Slides 40 to 42, from animations of a real table-sized sand model of a geologic cross-section (animation available on-line at <http://www.wda-consultants.com/page20.htm>) shows the same kind of flow pattern with recharge and discharge areas, and artesian flow in the discharge area. The flow patterns in the sand model are then successfully mathematically simulated in a vertical cross-section (slide 47) using permeability contrasts instead of actual permeability measurements.

Counterplay of forces

Mechanical force fields (the gradients of energy fields) drive all fluid flow in the subsurface in response to the gravitational energy. At the groundwater table the pressure potential energy is practically zero, when neglecting forces within the unsaturated zone. At this point, all the energy of the unit mass consists of gravitational energy. Any downward movement in the gravitational field frees a large amount of energy which is used to overcome the resistance to flow exerted by the rocks penetrated. The amount not used in overcoming this resistance to flow is stored within the unit mass as deformation (compression) of the unit mass. Water is slightly compressible and can store an extraordinary amount of energy when compressed. This stored energy is released when the water flows upward against the gravitational gradient and overcomes the resistance of the rock penetrated.

In slide 55, the application of the non-physics-based incompressible Navier-Stokes equation for surface water hydrodynamics is shown to be a phenomenological equation only. This equation should not be applied to fluid flow calculations in subsurface conditions nor should Muskat's (1937, eq. 3.3(3)) velocity potential equation even if it attempts to include gravitational forces (ibid., p.132) in an "awkward" (Payne et al., 2008, p.53) manner

Paradigm Shift Tóth, 1962: Groundwater flow systems – they penetrate that deep?

The use of vertical cross-sectional groundwater flow models has been pioneered by Tóth (1962) and Freeze and Witherspoon (1966, 1967) to arrive at the Theory of Groundwater Flow Systems and to document the effect of topography and geological structures on groundwater flow pattern. The authors elucidate the determinant role of the topography of the groundwater table and of the geological structures on the distribution of recharge and discharge areas as well as upon the pattern and depth range of groundwater flow systems.

Tóth (1962) showed how an undulating groundwater table (amplitude 15 m; total slope 125 m over 6 km) caused, in homogeneous and isotropic rocks, groundwater flow systems to penetrate to 3000 m depth. Tóth (2009), in a new book on gravitational systems of groundwater flow, while summarizing much of the present knowledge of the principle pattern of groundwater flow systems and their effect on geological processes, shows these systems to penetrate to depths of 5 km or more.

Freeze and Witherspoon (1966, 1967) used a dimensionless variable, S , for length and depth of the cross-sections used for simulating groundwater flow. This means that at a length of 10 km, the depth of flow would have been 1 km; at a length of 50 km, the depth of flow would have been 5 km deep. These limitations have been created by the choice of the length-to-depth ratio for the model, not by physical constraints.

It was thus shown that flow systems would penetrate to several kilometers depth and that, under natural conditions, more than twice as much water would flow through an overlying aquitard into and out of an underlying aquifer as was actually flowing within the aquifer (slides 59 [2] and 60 [2]). Weyer (1996) showed the ease with which one can visualize the actual upward and downward flow directions in an aquitard by comparing water levels in the buried aquifer with those at the groundwater table (slides 62 and 65). The additional example of 2D-vertical groundwater flow models [4] and [6] shows the groundwater flow in recharge areas penetrating deeply through clay layers (aquitards, aquicludes) into higher permeable layers and upward flow through the same layers to the discharge area at the surface [slides 73 and 83].

Silt [10^{-8} m/s, 1 mD] as an efficient hydraulic window

It is often assumed that, in the subsurface, hydraulic windows need to be highly permeable to be effective conduits for migration of groundwater. The field example and 3D-mathematical model [5] Hilden/Düsseldorf shows otherwise. The model simulated flow through a silt window that is surrounded by clay. A head difference of 15 m (from the groundwater table to the underlying Devonian dolomite layers) and a permeability difference of about 1 order of magnitude in the aquitard layer was sufficient to draw much of the groundwater downwards into a higher-permeable layer of Devonian dolomite and from there towards a dewatering mine.

The example illustrates in which way permeability contrasts exert a forging influence on force fields and resulting flow directions in the subsurface.

7. Upward-discharging salt water and brine

*Many scientists and practitioners believe that salt water and brine would move to the bottom of groundwater flow systems and stay there as they **could not** move upwards due to the density differences. The mechanism assumed to be at work is also hydrostatic but opposite in effect to the upward-directed hydrostatic 'buoyancy' for fluids with a density $< 1 \text{ g/cm}^3$. Many computer codes have been written with the assumption that hydrostatic conditions apply to flow of salt water and brine when they actually behaved differently under hydrodynamic conditions. Again the hydrostatic concept of flow does not reflect reality.*

The field example and mathematical model [6] Münchehagen landfill in Germany showed the salt water flow pattern (density of ocean water) to be practically the same as that of fresh groundwater (slide 87). The system was of variable density in that recharged fresh groundwater picked up its salt load in marl with evaporitic parts at about 1000 m depth. Then it flowed upwards towards the landfill and turned at about 50 m depth towards the discharge area at the river Ils (slides 83 and 85). This result of the mathematical model was confirmed by salinity measurements in borehole 226 (slide 86). The results of the mathematical model were based on geology taken from public geologic maps in the scale 1:25,000 and were obtained in the first model run.

The second field example shows upward discharging saturated brine within the Salt River catchment basin, NWT, Canada (slide 88). There have to exist very high upward-directed fresh groundwater gradients. To overcome the gravitational force the freshwater pressure potential gradient needs to be $> 1.3 \cdot g$ (the gravitational force).

The third field example also stems from the Western Canadian Sedimentary Basin which contains several salt layers at depth. It shows salty water discharging at the southern shore of Great Slave Lake (slide 89). The investigation of this flowing borehole was part of a multi-year study dealing with the dewatering at Pine Point Mines.

8. Pressure potential forces versus 'buoyancy forces' (a misnomer)

There exists considerable confusion about the mechanism causing buoyancy under hydrostatic and under hydrodynamic conditions. In fact most, if not all, scientists and practitioners assume that the so-called 'buoyancy force' is directly dependant on differences in density only and is vertically directed upward in both hydrostatic and hydrodynamic conditions. Both assumptions are physically incorrect.

The hydrostatic conditions are a special case of hydrodynamic conditions whereby there is no flow occurring within the energy field created by gravitation within the water body. In fact the energy state throughout the hydrostatic water body is equivalent and no water flows. At all locations within the hydrostatic water body pressure potential gradients (forces) are equal to the gravitational gradient (force) and cancel each other as they are opposite in direction. Slide 93 shows the mechanism how the pressure potential force of the water is the vehicle to create upward-directed forces for less dense fluids (C:oil, D:gas) and downward-directed for denser fluids (A: salt water). On the right hand side of the hydrostatic slide 93 the

pressure potential forces for water, oil, and gas have been combined into one vector diagram showing how the upward forces for lighter material are created in the energy field of the water. Under hydrostatic conditions the combined vector diagram shows a vertically-upward direction; under hydrodynamic conditions it does not (slide 95).

*Slide 95 enforces that the generally non-vertical direction of the pressure potential gradient under hydrodynamic conditions necessarily implies that the pressure potential gradients for oil, gas, CO₂, salt water and brine are directed in the same direction as that of the fresh groundwater water due to the physical processes at work in the subsurface. The pressure potential gradients for oil, gas, CO₂, salt water and brine are therefore **not vertical** under hydrodynamic conditions. The actual flow directions are then determined by vectoral addition for each of the fluids as shown in slide 97.*

In general, under hydrodynamic conditions in the subsurface, the so-called 'buoyancy force' may be directed in any direction in space. Only under hydrostatic conditions is the so-called 'buoyancy force' (i.e. the pressure potential force) always directed vertically upwards. The use of the term 'buoyancy force' has been misleading many scientists and practitioners and should be discontinued.

The same hydrodynamic principle also applies to horizontal flow. There, the gravitational gradient is directed vertically downward, and by necessity the pressure potential gradient (force) is directed obliquely upwards in the direction of the horizontal flow. Typically that point is missed on presentations of model calculations as for example those presented at the GHGT9 and by the Princeton model [8] (slide 117). In fact, to our knowledge, there doesn't yet exist any model code which attempts to include the pressure potential force in a physically-correctly manner when calculating flow directions for oil, gas and CO₂. Existing model codes assume vertical hydrostatic conditions for what they call 'buoyancy force'. That needs to be corrected when dealing with the grand scale of CO₂ sequestration.

9. Paradigm shift: 'Buoyancy Reversal' [Weyer, 1978]

In areas with strong downward flow, the need to maintain the downward flow through 'aquifers' may have to balance its energy needs from the compressed unit mass if the gravitational energy gain (due to decrease in elevation) is not sufficient to maintain the necessary flow rate. Under these conditions, the pressure in the aquifer decreases with depth. These aquifers would then show a 'Buoyancy Reversal', a term created by Weyer (1978). 'Buoyancy Reversal' means that under these geologic and hydrodynamic conditions in the subsurface, the pressure potential force (the so-called 'buoyancy force') is directed downwards. These conditions have frequently been encountered in the Swan Hills area in Alberta and in other areas worldwide

10. Geological storage of CO₂

The first part of this section deals with the change within an oil reservoir from hydraulic sink conditions during production pumping to hydraulic source conditions as CO₂ is injected (slide 112). Within CCS activity, hydraulic monitoring would track the effect of these changes within the surrounding rocks (slide 114).

The second part of this section points out some shortcomings in the manner mathematical models have been applied to date to predict the migration behaviour of large scale CO₂ sequestration. The models shown ignore the physically-derived force fields in the subsurface. Instead one considers the hydrostatic “buoyancy force” (i.e. a vertical pressure potential force), and capillary pressure (slide 116) while the other considers hydrostatic conditions and horizontal flow by pressure gradients only (slide 117).

The third part of this section visualizes the omnipresence of boreholes in mature basins of North America and other continents. The abandonment procedures usually have been imperfect, leading to leakage problems for large scale CO₂ sequestration and its associated long term rise of pressure potentials. In spite of statements to the contrary, this is a situation not yet experienced when injecting fluids in parts of operating oil fields. We are confronted with a situation necessitating unbiased and encompassing treatment of the problem and risk assessments applied. Oil field operation has lowered the pressure potentials by the equivalent of many hundred meters of freshwater head (slides 112 and 123) and thereby created sinks for regional groundwater flow in the subsurface. With large scale CO₂ injection, these sinks will be turned into sources by increased pressure potential forces resulting in changed flow patterns in the subsurface. In this environment the role of microannuli will most likely be significant. The example calculation of downward fluid flow through microannuli (slide 124) has been based on actual head differences at Alberta well 8-16-41-1 (slide 123), assumptions about the opening width and vertical extent of the microannuli, and equations used within the oil industry.

The fourth part of this section communicates the results of 2D-vertical fresh groundwater flow models within geologic cross-sections taken from the real world. The field example and mathematical model [9] was part of an investigation leading to the 1992 ERCB hearing on the Hayter Field near Provost, Alberta (slide 128). The model assumed existing wells in the recharge area and discharge area to be leaking. Upon restoring the pressure potential distribution to its original conditions slide 131 shows how natural flow from the recharge area would penetrate through leaking wells into the reservoir, flow through the reservoir to leaking wells located in the recharge area and discharge through these wells towards the surface. The transport from the reservoir to the discharge area would eventually happen without any addition of CO₂ injection.

Field example and mathematical model [10] refers to an investigation in Central Alberta (slide 132). A farmer experienced salting of his water supply. The results of the mathematical model showed the changes in flow pattern of fresh groundwater which would be caused by the existence of one leaking well near the Vermillion River. The model made it conceivable that salt water had been migrating up from the reservoir into the farmer’s aquifer.

In general, partially abandoned wells create hydraulic shortcuts in aquitards above the sealed area of ‘caprocks’ and thereby considerably increase the overall regional permeability of the total aquitard system and also increase the amount of hydrous flow through caprocks.

Conclusions

The conclusions are grouped under the headings *Fluid flow*, *Capillary forces*, *Mathematical models*, and *Effect of well abandonment on CO₂ sequestration*.

Fluid flow

- For CO₂ sequestration, fluid flow in the subsurface should be dealt with using Hubbert's (1940) Force Potential.
- Fluid flow in the subsurface is governed by mechanical fields created by fresh water. These fields are partially modified by raising the pressure potential at CO₂ injection sites.
- Groundwater flow systems penetrate into the depths of deep well disposal.
- Groundwater flows in great amounts through aquitards and should be considered when dealing with CO₂ sequestration.
- Saline water flows upwards into discharge areas, as did brines in the basin of the Salt River, NWT, Canada. Salt water does not segregate and sink to the bottom of the geologic system.
- Flow of ocean-type saline water can be modelled by fresh water models as the fresh water force field determines the general force directions.
- Operating CO₂ sequestration sites should be monitored by a network of deep piezometer nests in addition to other methods.

Capillary forces

- Capillary forces should be dealt with in the manner described by Hubbert [1953].
- Capillary forces are capillary pressure potential gradients within non-hydrous fluids, not capillary pressure or capillary pressure gradients.
- Capillary forces at fluid interfaces should be determined in direct dependence upon the details of the sedimentary sequence between aquifers and aquitards and its geometry.

Mathematical models

- Mathematical models presented in IPCC [2005] and others do not take the force fields of gravitational Groundwater Flow Systems into account but should do so.
- Hydrodynamic model codes utilizing vertical 'buoyancy forces' instead of pressure potential forces are insufficient.
- Mathematical models making use only of pressure gradients and/or hydrostatic pressure are physically flawed, and lead to incorrect results in the direction, magnitude, and velocity of flow. They should be avoided.

- There is a need for modification of existing model codes to ensure full and simultaneous integration of gravitational, pressure potential and capillary forces.

Effect of well abandonment on CO₂ sequestration

- The large number of existing oil wells pose a direct risk to CO₂ sequestration due to widespread imperfect abandonment procedures.
- Risk assessments should consider all affected wells in a field and in nearby areas for leakage into and out of a reservoir. In North America the number of affected wells at sequestration sites often exceeds several hundred.
- Flow through microannuli in abandoned wells should be considered in any form of risk assessment for CO₂ sequestration. Upward flow of CO₂-saturated fluids through microannuli likely increases the corrosion of annulus cement significantly. In turn corrosion of annulus cement would increase the flow of CO₂-saturated fluids significantly.

Credits

The work on the basics of hydrodynamics was originally supported directly or indirectly by

- the German Research Foundation [DFG], Bonn, Germany,
- the Centre d'Hydrogéologie a l'Université de Neuchâtel, Switzerland,
- the Hydrology Research Division [HRD] of the Canadian Federal Department of Environment, Ottawa, Canada, and,
- the hydrogeology and engineering geology sections of the Bureau de Recherches Géologiques et Minières [B.R.G.M.] in Orléans-la-Source [France]

Further development was done as an employee in the Hydrology Research Division [HRD] of Environment Canada in Ottawa and Calgary, and, for more than 20 years within my companies WDA Consultants Inc, Calgary, Canada and WKC Consultants, Krefeld, Germany. The Umweltbundesamt [German EPA] of the German Federal Department of Environment supported a research project on these matters, culminating in a German language report [Weyer, 1996] summarizing the basics of groundwater flow using Hubbert's Force Potential and efficient methods for investigating deep-penetrating groundwater flow systems.

Ongoing discussions with James C. Ellis, WDA Consultants Inc., have been very helpful in re-testing and elucidating the physical validity of the concepts applied to carbon storage.

We are particularly indebted to the generosity of Petrobras and the scientific foresight of Dr. Paulo Cunha, Coordinator for CCS at the Petrobras R&D Center for the invitation to present at the 2nd Petrobras International Seminar on CO₂ Capture and Geological Storage, 09-12 September 2008 - Salvador/BA – Brazil. The preparation for this seminar precipitated my ongoing involvement in carbon storage and the preparation of this primer.

This primer was also strongly influenced by papers presented and numerous discussions with participants at GHGT-9 (Washington D.C., November, 2008), the CO₂ Geological Storage Modelling Workshop (Orléans, February 2009), the CO₂GeoNet Open Forum (Venice, March 2009), the CO₂ Risk Assessment Workshop (Melbourne, April 2009), the Wellbore Integrity Workshop (Calgary, May 2009), and the CO₂ Monitoring Workshop (Tokyo, June 2009). Thanks is due to all the organizers of the above conferences, in particular the IEA GHG (Cheltenham, England) who organized the very informative workshops in Orléans, Melbourne, Calgary and Tokyo.

The ensuing discussions at 10 invited presentations of this material at scientific seminars, universities, and corporations in Brazil, Canada, Germany, the Netherlands, Australia and Japan also greatly helped to refine this primer and we are grateful to those who made this possible.

List of References

[The references refer to Part 1 and 2.]

- Albinet, M., and S. Cottez, 1969. Utilisation et interprétation des cartes de différences de pression entre nappes superposés. *Chronique d'Hydrogéologie*, Nr. 12, S.43–48, B.R.G.M., [Paris] Orléans
- Celia, M.A., S. Bachu, J.M. Nordbotten, S.E. Gasda, and H.K. Dahle, 2004. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7), vol. 1, p.663-672
- Darcy, Henry, 1856. *Les fontaines Publiques de la Ville de Dijon*. Victor Dalmont, Paris.
- de Vries, J.J., 2007. History of groundwater hydrology. Chapter 1 in J. W. Delleur, 2007. *The Handbook of Groundwater Engineering*, 2nd Ed, CRC Press.
- Driscoll, Fletcher G., 1986. *Groundwater and Wells*, 2nd Edition. Johnson Division, St. Paul, Minnesota, p.67, table 5.1.
- Economides, M. J., 1990. Implications of cementing on well performance. Chapter 1 in E.B. Nelson, 1990. *Well Cementing*. Schlumberger Educational Services, Houston, Texas.
- Freeze, R.A. and J. A. Cherry, 1979. *Groundwater*. Prentice-Hall Inc., Englewood Cliffs, N.J., 07632.
- Freeze, R.A. and P.A. Witherspoon, 1966. Theoretical analysis of regional groundwater flow: 1. Analytical and numerical solutions to the mathematical model. *Water Resources Research*, vol.2, no.4, p.641-656
- Freeze, R.A. and P.A. Witherspoon, 1967. Theoretical analysis of regional groundwater flow: 2. Effect of water table configuration and subsurface permeability variation. *Water Resources Research*, vol.4, no.3, p.581-590.
- Gasda, Sarah, J. Nordbotten, and M. Celia, 2008. Determining effective wellbore permeability from a field pressure test: a numerical analysis of detection limits. *Environmental Geology*, Volume 54, Number 6, May 2008 , p. 1207-1215(9).
- Gallavotti, G., 2002. *Foundations of fluid dynamics*. Springer-Verlag, Berlin, Heidelberg, 536 p.

- Gronemeier, K., H. Hammer, and J. Maier, 1990. Hydraulische und hydrodynamische Felduntersuchungen in klüftigen Sandsteinen für die geplante Sicherung einer Sonderabfalldeponie [Hydraulic and hydrodynamic field studies in fractured sandstone for safe disposal of special industrial waste]. Zeitschr. dt. geol. Ges., vol.141, p.281-293, Hannover
- Hitchon, B, C.M. Sauveplane, S. Bachu, E.H. Koster, and A.T. Lytviak, 1989. Hydrogeology of the Swan Hills Area, Alberta: Evaluation for deep waste injection. Alberta Research Council Bulletin No. 58.
- Hubbert, M. King, 1940. The theory of groundwater motion. J.Geol., vol.48, No.8, p.785-944.
- Hubbert, M. King, 1953. Entrapment of petroleum under hydrodynamic conditions. The Bulletin of the American Association of Petroleum Geologists, Vol. 37, No. 8, August 1953.
- Hubbert, M. King, 1957. Darcy's law and the field equations of the flow of underground fluids. Bulletin de l'Association d'Hydrologie Scientifique, No. 5, 1957, p.24-59.
- Hubbert, M. King, 1969. The theory of groundwater motion and related papers. Reprints of 3 papers with corrections plus 1856 paper by Henry Darcy. With a new introduction by the author. Hafner Publishing Company, 311 pages.
- International Panel on Climate Change [IPCC], 2005. Carbon dioxide capture and storage. IPCC special report. 429 pages, Cambridge University Press.
- Jacob, C.E., 1940. On the flow of water in an elastic artesian aquifer. Transactions, American Geophysical Union., Vol. 21, p. 574-586.
- Jutten, J., and S. L. Morriss, 1990. Cement job evaluation. Chapter 16 in E.B. Nelson, 1990. Well Cementing. Schlumberger Educational Services, Houston, Texas.
- Kiraly, L., 1975. Rapport sur l'état actuel des connaissances dans le domaine des caractères physiques des roches karstiques. In: Hydrogeology of Karstic Terrains, International Union of Geological Sciences , Series B, Nr.3, p.53-67, published by the International Association of Hydrogeologists, Paris, 1975.
- Kuhn, T.S., 1970, The structure of scientific revolutions, 2nd Edition. University of Chicago Press, Chicago, London, 222 pages.
- Lüdeke, H., 1987. Sicherungs- und Sanierungsmaßnahmen auf der Soderabfalldeponie Münchehagen [Safety and restoration preventative measures at the special waste landfill Münchehagen]. Müll und Abfall, vol. 19(6), p.240-248 (Figures p.242 and p.243), Berlin, Bielefeld, München.

- Muskat, Morris, 1937. The flow of homogeneous fluids through porous media. McGraw-Hill Book Company Inc.
- Payne, F. C., J. A. Quinnan, and S. T. Potter, 2008. Remediation Hydraulics, CRC Press, Boca Raton, Florida.
- Planck, M., 1948. Wissenschaftliche Selbstbiographie. Barth, Leipzig.
- Segall, P., 1989. Earthquakes triggered by fluid extraction. *Geology*, vol.17, p.21-42
- 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. Leakage of CO₂ through abandoned wells: role of corrosion of cement. *Carbon Dioxide Capture for Storage in Deep Geologic Formations*, Vol. 2, p.827-848. Elsevier Ltd., Amsterdam.
- Schoonbeek, J.B., 1977. Land subsidence as a result of gas extraction in Groningen, The Netherlands. *Proceedings of the 2nd International Symposium on Land Subsidence*, Anaheim, Ca. IAHS-AISH publication No.121, p.267-284.
- Slichter, C.S., 1899. Theoretical Investigation of the Motion of Ground Waters. *Nineteenth Annual Report of the United States Geological Survey, Part II*, p.295-384.
- Tóth, J., 1962. A theory of groundwater motion in small drainage basins in Central Alberta, Canada. *J. Geophys. Res.*, vol.67, no.1, p.4375-4387.
- Tóth, J., 2009. *Gravitational systems of groundwater flow; Theory, Evaluation, Utilization*. Cambridge University Press, 297 p.
- Waltz, J.P., 1973. Ground Water. S.122–130 in: Chorley, R.J., 1973. *Introduction to physical hydrology*. 211 S., Methuen & Co. Ltd., London.
- Weyer, K.U., 1978. Hydraulic forces in permeable media. *Mémoires du B.R.G.M.*, vol. 91, p.285-297, Orléans, France. [*The reference Weyer, 1978, is available for download from the website <http://wda-consultants.com>.*]
- Weyer, K.U, 1992. Written submissions as expert witness to the ERCB Hearing Re: Battery Site at Provost – 16-41-01 W4M (Simon and Michael Skinner v. AMAX Petroleum of Canada Inc.), Jan. to Apr., 1992.
- Weyer, K.U., and A.M. Altebäumer, 1993. *Impact of the Petroleum Industry on Cattle Raising in Alberta – Critical Literature Review and Data Report*. Consultants report, Vol.1: Text, 291 p.; Vol.2: Figures, Tables, Appendices. 215 p., December 9, 1993.

- Weyer, K.U., 1996. Physics of groundwater flow and its application to the migration of dissolved contaminants. [Darlegung und Anwendung der Dynamik von Grundwasserfließsystemen auf die Migration von gelösten Schadstoffen im Grundwasser]. Final Research report to the Federal Environmental Office [Umweltbundesamt] of the German Government [Res.Proj. 102 02 632]. 204 pages, 79 fig., 16 photographs, 15 tab.: April 1996 [in German]. [*The reference Weyer, 1996, is available for download from the website <http://wkc-consultants.com>.*]
- Weyer, K.U. and J.W. Molson, 2004. 2D- and 3D-model calculations for optimizing remediation wells in Hilden/Düsseldorf, Germany (Modellrechnungen für die Planung von Sanierungsbrunnen im Grenzbereich Hilden/Düsseldorf). Consultant report to the County of Mettmann [in German]. 128 p., 73 Fig., 5 Tab.
- Weyer, K.U., 2006. Hydrogeology of shallow and deep seated groundwater flow systems. Primer for clients, 19 p. [*The reference Weyer, 2006, is available for download from the website <http://wda-consultants.com>.*]