Edited Word version of a poster shown at IEA GHG Joint Network Meeting, Santa Fe, NM, June 19-21, 2012

Applying Gravitational Forces to the Weyburn CO_2 Sequestration: Expanding Hydraulic Research and Applications for the Benefit of Future Generations.

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Weyburn investigations to-date: Applying Muskat's Velocity Potential

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

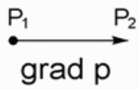
$$\mathbf{v} = -(k/\mu) \, grad \, p$$

volumetric flow vector — intrinsic permeability / dynamic viscosity — pressure gradient

Muskat, 1937

These equations are not valid expressions of Darcy's Law.

Force calculation for horizontal flow

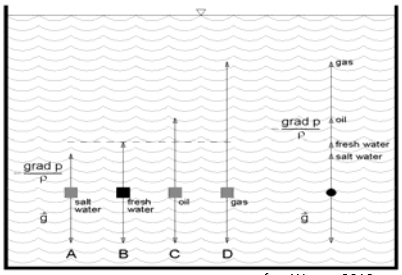


$$Q = A \frac{K}{\mu} \frac{P_1 - P_2}{L}$$

vectorial addition not used

Pirson, 1977, p.389: "*The force of gravity is ineffectual as a source of driving energy and the gravity term drops out of the flow equation.*" This opinion is erroneous as it disregards the gravitational force vectors omnipresent on earth.

Hydrostatic Buoyancy



after Weyer, 2010a

A = downward flow for dense salt water..... (grad p)/ρ < g

B = no flow for fresh water........................... (grad p)/ρ = g

C = upward flow of oil...................................(grad p)/ρ > g

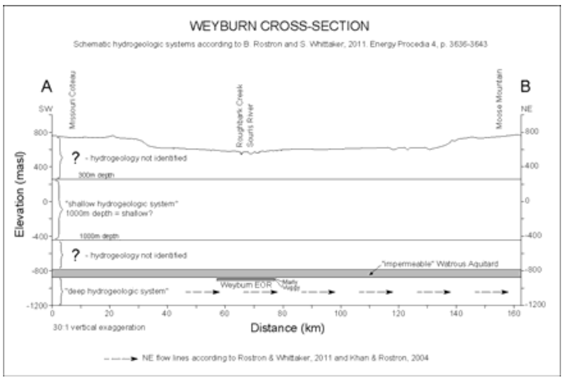
D = upward flow for gas............................... (grad p)/ρ >> g

- pressure potential gradients in vertical directions
- "buoyancy" flow in vertical directions

The use of hydrostatic buoyancy under hydrodynamic conditions is one of the bases of so-called "variable density flow' calculations.

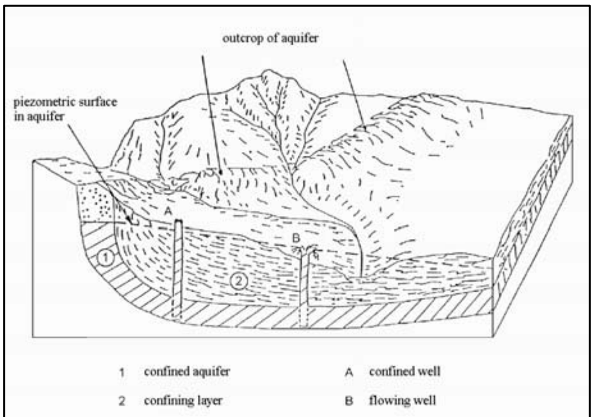
Groundwater flow at Weyburn

(Watrous aquitard assumed to be impermeable)



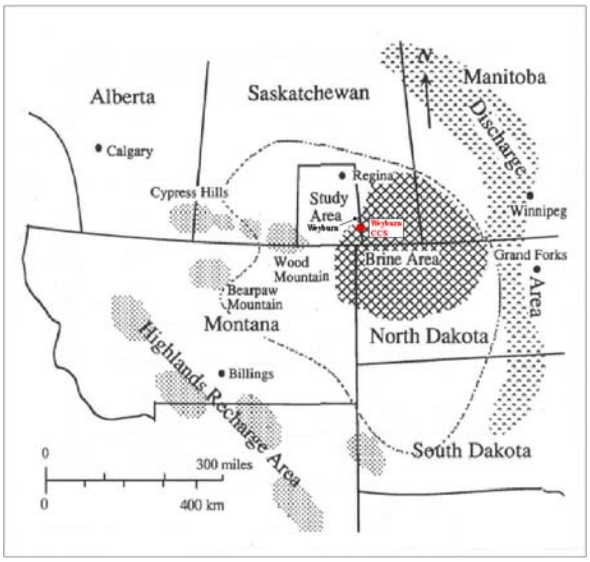
The diagram summarizes the conceptual approach outlined by Khan and Rostron (2004) for the hydrogeological framework at the region of the Weyburn oil field. Below the Watrous aquitard, groundwater supposedly flows in the Midale from SW to NE, and does not penetrate the Watrous upwards towards Souris River and Roughbark Creek. The flow in the Mississippian formation (containing the Midale) migrates from the SW under the Wood Mountain and towards the NE under the Moose Mountain ridge.

A depth of 200 to 1000 m below surface is considered to be shallow groundwater.



Waltz, 1973, Fig. 6.1.3

The erroneous approach taken by Waltz (1973) appears to be a convenient and persistent concept applied to regional groundwater flow with artesian conditions. Freeze and Witherspoon (1967) proved this opinion to be incorrect.



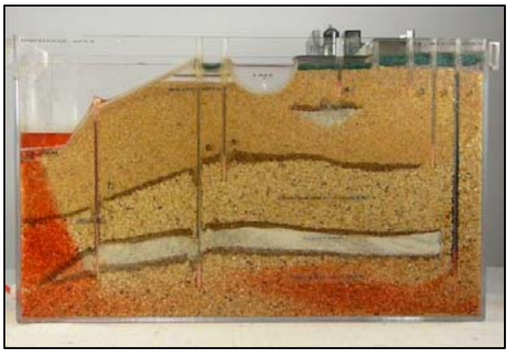
After Toop and Tóth, 1995 (after Downey et al., 1987)

Deep groundwater flow has been assumed to be from as far away as the Big Horn Mountains and the Yellowstone National Park in Wyoming (Downey et al., 1987; Hannon, 1987; Bachu and Hitchon, 1996; Khan and Rostron, 2004). These distances are, however, physically infeasible, as they offends the principle of minimization of energy use within a flow field. Instead the deep groundwater is intersected by the valleys of the Missouri River and its tributaries.

Under nearer recharge areas as the Wood Mountains, the Missouri Coteau and the Moose Mountain ridge, groundwater flow systems penetrate the Watrous aquitard and enter the Mississippian layers. At Weyburn the deep groundwater flow is intersected by the valleys of the Souris River and Roughbark Creek. The elevation differences between the regional recharge areas Moose Mountain ridge to the NE and the Missouri Coteau to the SE are higher by up to 230 m and 400 m respectively. Suitable mathematical models have so far not been calculated for the Weyburn CO_2 sequestration studies.

Reality check:

from Weyer, 2010b, Fig. 13



from Weyer, 2010b, Fig. 14

Crystal Geyser, Green River, UT

Dissolved CO_2 migrates with deep saline groundwater flow systems and discharges from below into the water courses as indicated by the discharging well and the coning in the sand model.

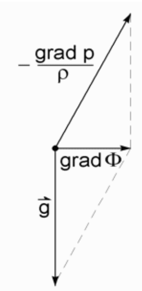
Weyburn in the future? Applying Hubbert's Force Potential

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

fluid force — gravitational force — pressure potential force (buoyancy force)

Hubbert (1940, 1953, 1967, 1969)
These field equations lead to valid expressions of Darcy's Law by field equations (Hubbert, 1957)

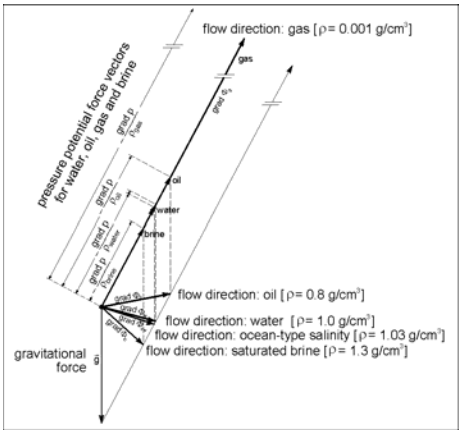
Force calculation for horizontal flow



$$Q = A \frac{K}{\mu}\ grad\ \Phi$$

vectorial addition always applied in calculation of hydraulic forces

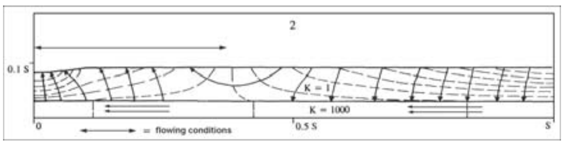
Hydrodynamic Buoyancy



after Hubbert, 1953, Fig. 11

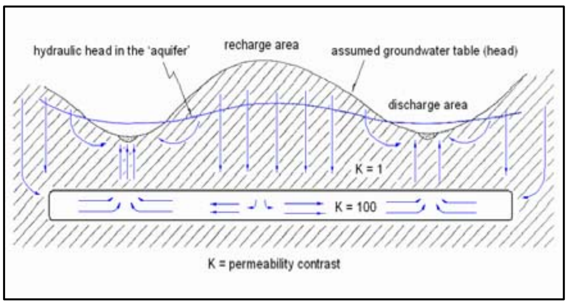
- pressure potential vectors (the buoyancy forces) may be in any direction in space, including vertically downwards (Buoyancy Reversal, Weyer, 1978)
- the direction of the pressure potential force for fresh groundwater determines the direction of pressure potential forces for saline water, hydrocarbons and supercritical and gaseous CO_2.
- groundwater may flow in any direction in space

Groundwater flows through aquitards



from Freeze & Witherspoon, 1967, Fig. 7

Under natural conditions, twice as much groundwater may flow downwards and upwards through the aquitard as laterally in the aquifer. The equation of continuity is satisfied.

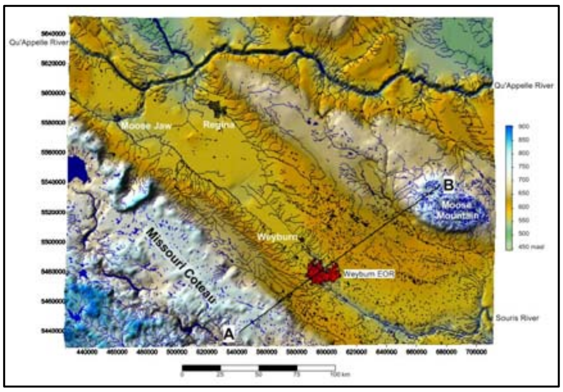


from Weyer, 2006, Fig. 10

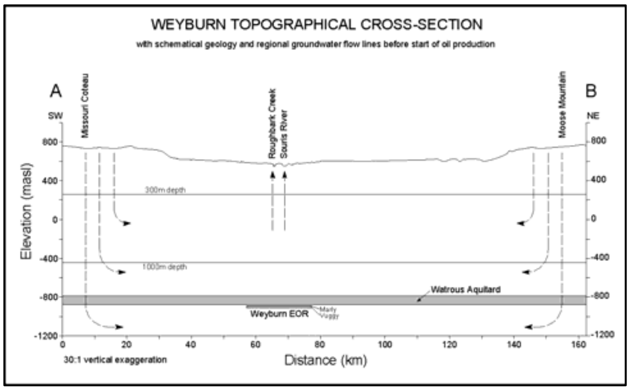
Direct proof of groundwater flow through aquitards: heads in the aquifer reflect topography. In recharge areas the head in the aquifer is lower than the groundwater table; in discharge areas the head in the aquifer is higher than the groundwater table. Artesian conditions (flowing wells) occur in discharge areas. These configurations have been confirmed at many sites worldwide.

Groundwater flow at Weyburn

(Watrous aquitard is permeable)

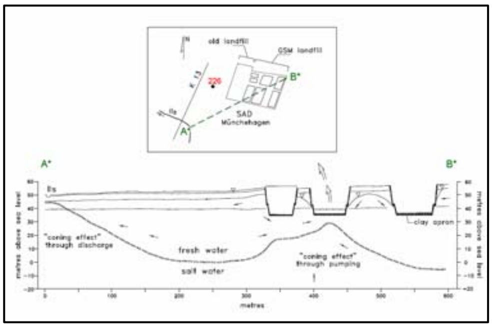


from Weyer, 2010b, Fig. 11

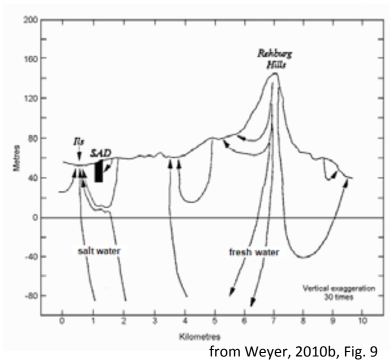


Modified from Weyer, 2010b, Fig. 12

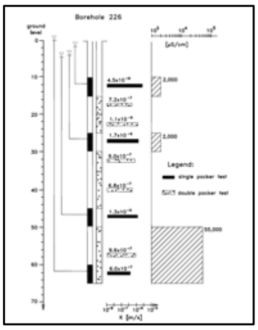
The Weyburn field is positioned within the topographical depression and a regional groundwater discharge area between the Missouri Coteau and the Moose Mountain ridge in the head water area of Souris River and Roughbark Creek. Hubbert (1967) reported for the Midale Beds of the Weyburn field a tilt of about 9 m/km in the southern direction for the oil/water interface according to exploration data by Socony-Mobil. Pre-production groundwater flow was also directed towards the south. In other parts of the Mississippian layers within the Weyburn field groundwater flow was directed towards the NE. Khan and Rostron (2004, p.747) dismissed clear indicators for upward flow from the Weyburn field into the overlying Watrous aquitard because they considered a hydraulic discontinuity “the more likely interpretation of the break” [of vertical pressure data]. Considering that in the Weyburn field, flow from the north and southwest met under natural pre-pumping conditions, and indicators of upward flow into the Watrous aquitard are present, an impartial judgement would consider the occurrence of salt water coning (upward flow) to be a definite possibility to be investigated for CO_2 storage. Post-sequestration groundwater flow systems are likely to resemble pre-production pattern.



from Weyer, 2010b, Fig. 7



from Weyer, 2010b, Fig. 9



from Weyer, 2010b, Fig. 8

Coning effects by discharge and well pumping Variable density flow lines Salt water

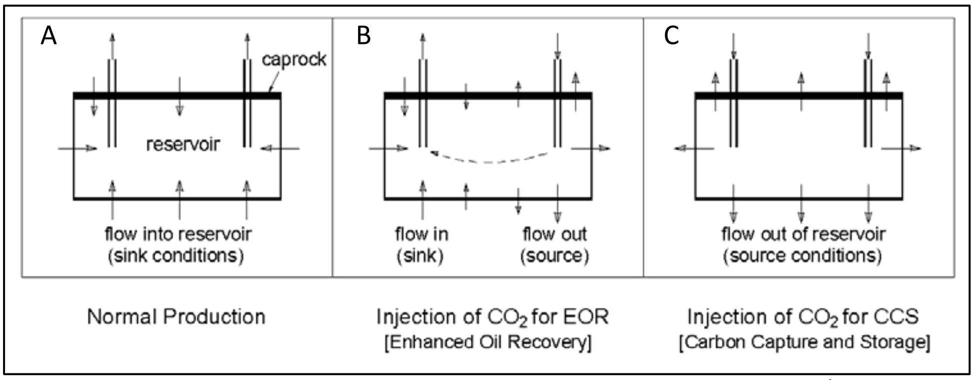
Weyer and van Everdingen (1995) described a coning effect with a ocean-level density (1.03 g/cm^3) of saline water at a site in Europe and calculated the variable density flow lines with a singular density model (1.00 g/cm^3). The results reflected independently taken chemical and borehole data very well. The depth of the deep flow systems reached about 1 km with the elevation of the recharge area about 80 m higher than that of the discharge area.

END OF POSTER PRESENTATION

Additional Explanations and List of References shown at the Conference with the Poster

- Reservoirs: Change from sink to source conditions
- Continuity of flow between aquitard and aquifer
- Superposition of Toop & Tóth (1995, Figure 13) upon a DEM of the region
- References

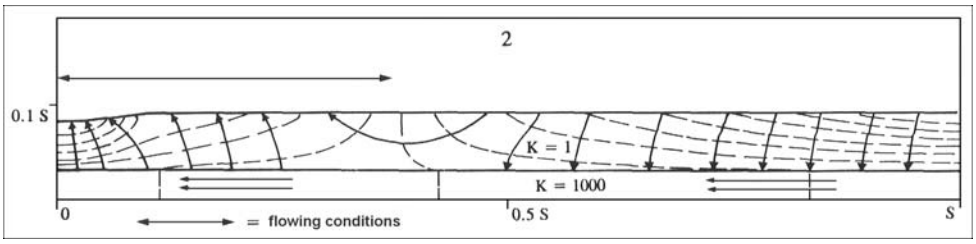
Reservoirs: Change from sink to source conditions



from Weyer, 2010a

Oil field simulators have been successfully applied for the sink conditions of part A. The application of oil field simulators will not calculate rigorously flow lines under the sink and source conditions of part B. Oil field simulators are unsuited to be applied under the source conditions of part C, due to physical code limitations and the assumption of artificial boundary conditions.

Continuity of flow between aquitard and aquifer (quoted from Weyer, 2010a)



from Freeze & Witherspoon, 1967, Fig. 7

Flow volume [q] entering aquifer

q	=	- grad Φ	*	A	*	σ
	=	hydraulic force	*	area	*	fluid conductivity

and given that: Flow leaving aquitard at base = Flow entering aquifer,

therefore flow is balanced by the following co-existing inequalities:

(1)	$\sigma_{aquitard}$	<<	$\sigma_{aquifer}$
(2)	$A_{aquitard}$	>>	$A_{aquifer}$
(3)	grad $\Phi_{aquitard}$	>>	grad $\Phi_{aquifer}$

The flow between aquitard and aquifer needs to be balanced as otherwise, unbalanced flow would lead to an accumulation of water at the boundary between the two layers.

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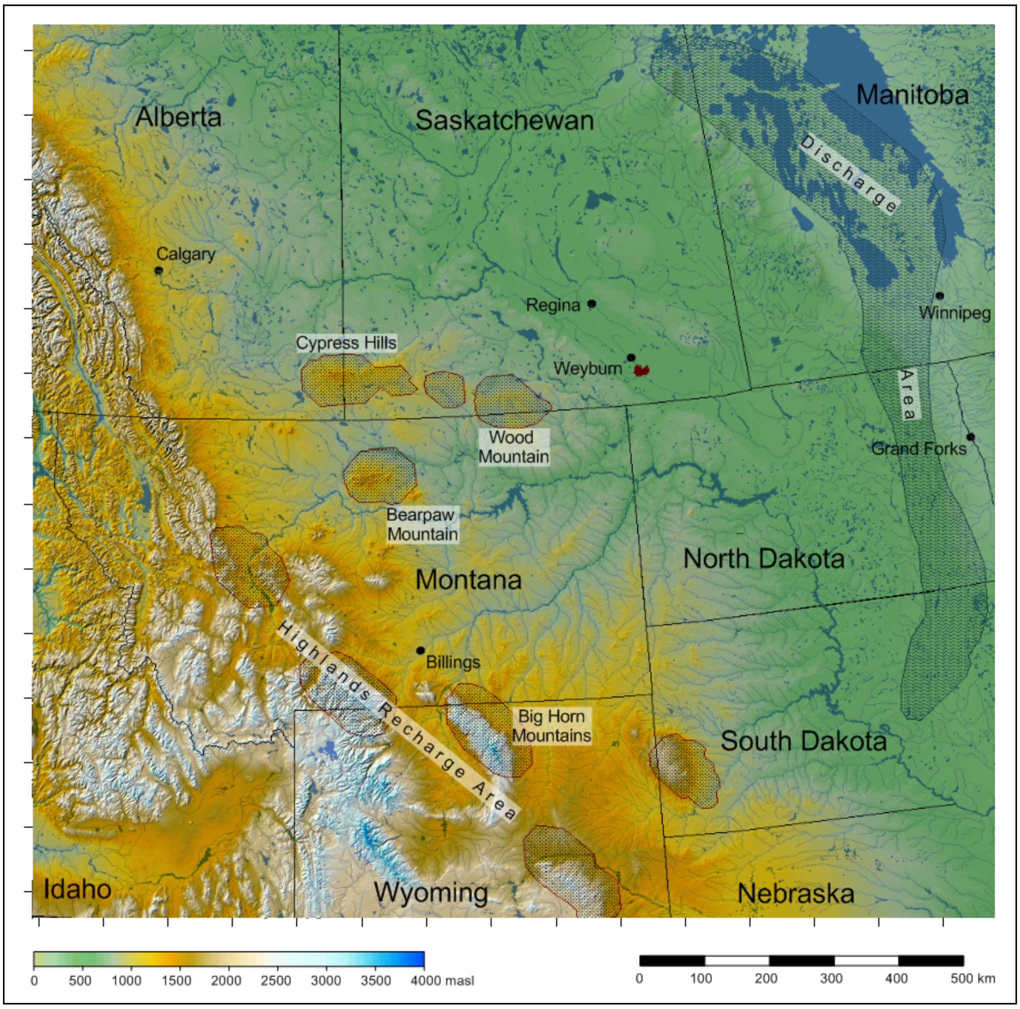
Superposition of Toop & Tóth (1995) Figure 13 upon a DEM of the region



Digital Elevation Model [DEM] of the map by Toop & Tóth (1995) shown above. Their recharge and discharge areas are superimposed on the DEM, showing that the discharge areas Yellowstone River and Missouri River and a number of high recharge areas are in the path of long distance groundwater flow to the Weyburn field (red area), assumed by Downey et al. (1987), Hannon (1987), Bachu and Hitchon (1996), and Khan and Rostron (2004) to occur in the Mississippian formation underneath the Watrous aquitard.

The DEM is based on electronic 1000 m grid elevation data derived from the ASTER GDEM (1.5 arc-second resolution) provided by NASA/METI. The recharge areas Missouri Coteau and Moose Mountains are located SW and NE of the Weyburn field respectively.

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