International Symposium on Regional Groundwater Flow:
Theory, Applications and Future Development

Practical Application of Buoyancy, Pressure Potential and Buoyancy Reversal within the Context of Regional Groundwater Flow

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1. Introduction

Within the context of regional groundwater flow, pressure gradients and buoyancy forces play a central role in judging hydrocarbon migration and carbon sequestration, be it in the determination of flow directions for both hydrocarbons and CO_2, or the determination of the height of breakthrough columns for CO_2. This paper deals with the application of physically correct force fields [*Hubbert*, 1940, 1953] to subsurface flow and its consequences. The methodology shown applies to both CO_2 sequestration and hydrocarbon accumulations. Its consequences are here shown using CO_2 sequestration as an example.

Vertical 'buoyancy', driven by density differences, is an integral part of Continuum Mechanics. Consequently fluids lighter than water (such as hydrocarbons and CO_2) are always thought to rise vertically upwards and fluids heavier than water are thought to sink and come to rest at the bottom of the geologic layer packets. These assumptions are based on a prevalence of hydrostatic subsurface conditions which is only the case off-shore; on-shore hydrodynamic conditions prevail [*Weyer*, 2010]. This paradigm shift, however, has so far been ignored in the praxis of CO_2 sequestration.

2. Application of Hubbert's Force Potential

Hubbert [1953] showed the basic difference between hydrostatic no-flow and hydrodynamic flow conditions (Figure 1). In the hydrostatic case, the gravitational force and the pressure potential force are of exactly the same magnitude but pointing in opposite directions. The resultant force '–grad Φ' (E in Hubbert's terminology) is zero and no flow occurs. In the general hydrodynamic case the gravitational force and the pressure potential force normally do not assume opposite directions and are not of equal magnitude. Therefore the resultant force vector is unequal to zero and flow occurs. In this case the 'buoyancy force' is rarely directed vertically upwards but rather in an oblique direction as the 'buoyancy force' is the pressure potential force ($-1/\rho \cdot \text{grad } p$). The pressure potential force can point in any direction in space including vertically downward (see below).

For the determination of hydrostatic conditions, low velocities and/or low amounts of flow are irrelevant. The direction of the so-called 'buoyancy force' is determined by the force field, not by the flow field. At any point in a low-permeable environment, the flow of groundwater may be slow and of minor amounts, but the associated pressure potential forces will be high and will determine the direction of 'buoyancy'.

Hubbert [1953, p.1960] showed that force potentials (energy/unit mass) of fresh groundwater determine the flow behaviours of other fluids such as air, salt water, oil, or gas (including CO_2 in liquid or gaseous form).

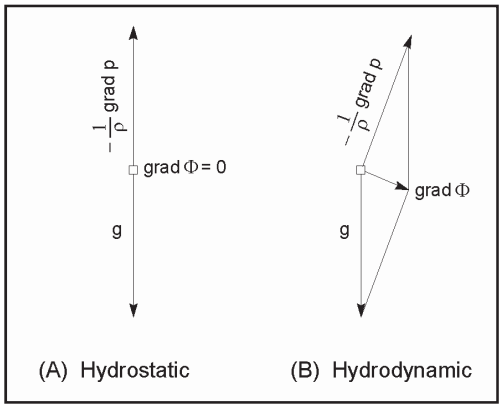

Figure 1. Hydrostatic forces versus hydrodynamic forces [after *Hubbert*, 1953, Figure 4].

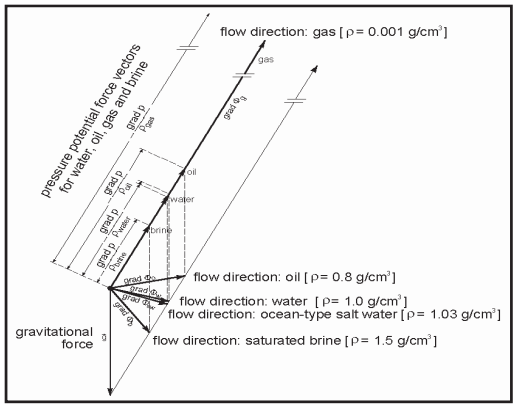

Figure 2. Schematic determination of flow directions for different fluids within the same fresh water field.

3. 'Buoyancy' under Hydrostatic Conditions

Under the subsurface hydrostatic conditions of the off-shore environment, fluids lighter than fresh water have a longer pressure potential vector than the fresh water vector and move upwards, while heavier fluids have a shorter pressure potential vector and move downwards. The resultant calculation leads to these results.

4. 'Buoyancy' under Hydrodynamic Conditions

Under hydrodynamic conditions, the pressure potential force ('buoyancy force' in the terminology of Continuum Mechanics) may take any direction in space. Again fluids lighter than fresh water will have a longer pressure potential vector, and those heavier a shorter pressure potential vector. The resultant calculation of the pressure potential vector and the gravitational vector now results in differing resultant force vectors determined by the same fresh groundwater force field.

Figure 2 shows the differing flow directions of various fluids within the same fresh groundwater force field, as determined by vectoral addition. As a consequence, the so-called vertically upward (density $\rho < 1$ g/cm^3) and downward ($\rho > 1$ g/cm^3) directed 'buoyancy forces' do not exist under hydrodynamic conditions.

5. Buoyancy Reversal

Due to energy considerations, 'Buoyancy Reversal' was postulated by *Weyer* [1978] for strong downward flow through low-permeable layers. In such a case, the pressure can decrease with depth (Figure 3, middle layer). These conditions occur when energy has to be taken from the compressed groundwater to maintain the amount of flow through low permeable layers such as aquitards and caprocks, thus causing reductions in pressure. In the Swan Hills area of Alberta (Figure 4), the result of independent field measurements (Figure 5) confirmed the existence of 'Buoyancy Reversal.' Figure 6 gives the geologic context within a cross-section.

Mathematically, the occurrence of 'Buoyancy Reversal' has been modeled by Frind and Molson [2010]. Buoyancy reversal occurs under recharge areas, while overpressure occurs under discharge areas as shown by the pressure-head profiles (Figure 7). It is remarkable that in both cases the drop of pressure within the aquitard (caprock) is not an indicator of any barrier function within the aquitard (caprock) as assumed by *Hitchon et al.* [1989]. Hydrous fluids flow right through the aquitard (caprock). The aquitards and caprocks are penetrated by the hydrodynamic force fields and are integral parts of regional groundwater flow systems.

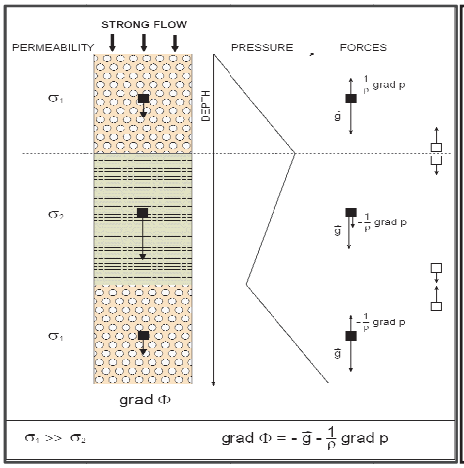

Figure 3. Distribution of forces at 'Buoyancy Reversal'.
grad Φ = hydraulic force
$-\vec{g}$ = gravitational force
-(grad p)/ρ = pressure potential force

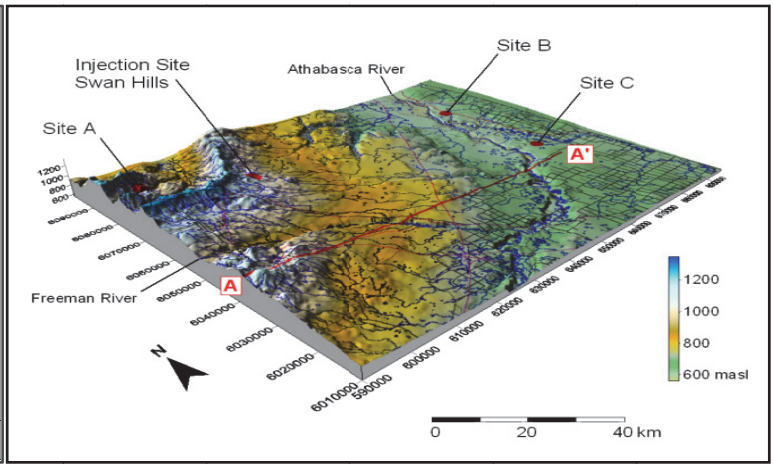

Figure 4. Digital Elevation Model [DEM] of the Swan Hills area, Alberta. The geologic cross-section A-A' (in Figure 6) is marked as a red line. At the marked sites A, B, and C, the occurrence of 'Buoyancy Reversal' was measured within the Clearwater-Wilrich aquitard.

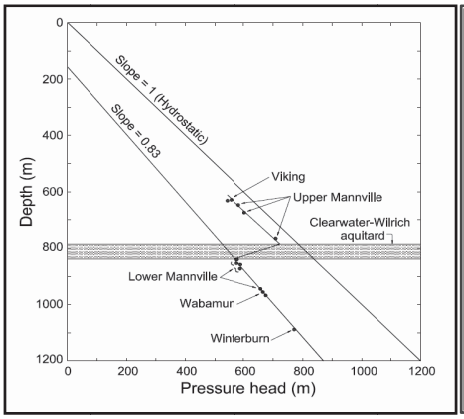

Figure 5. 'Buoyancy Reversal' at Site C within the Clearwater-Wilrich Aquitard [after *Hitchon et al*., 1989].

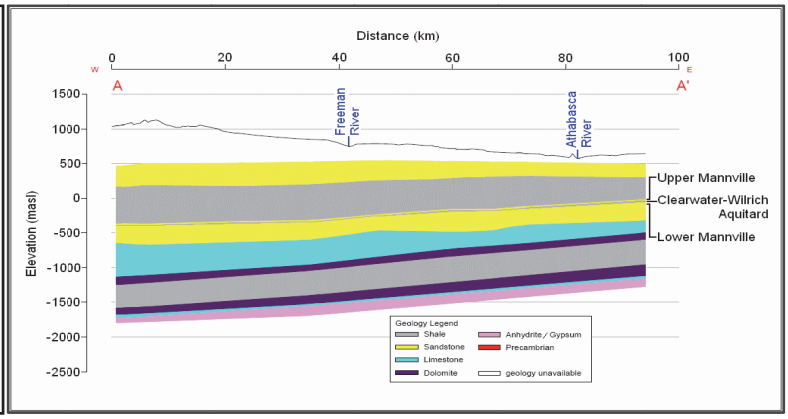

Figure 6. Geologic cross-section A-A'.See Figure 4 for location of cross-section.

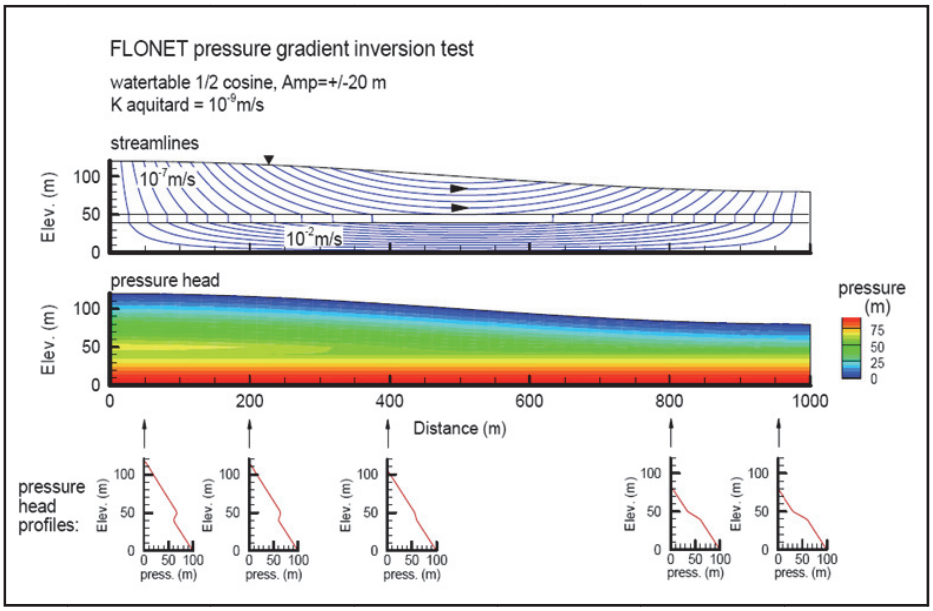

Figure 7. Natural groundwater flow system penetrating an aquitard creatingpressure reduction in the aquitard and thereby 'Buoyancy Reversal' underthe recharge area with downward flow. [Figure from *Frind & Molson*, 2010].

6. Conclusions

The existence of 'Buoyancy Reversal' has been proven by theoretical derivation, field evidence, and mathematical modeling. It prevails widely under recharge areas for regional groundwater flow but not in areas where discharge of regional systems prevail (Figure 7). Because of the mechanism of 'Buoyancy Reversal,' sequestration of CO_2 encounters more manageable conditions under recharge areas than under discharge areas. Its effect on the trapping and migration behaviour of hydrocarbons is also profound but has not yet been investigated in the field. The oil industry works with the mathematical 'physics' of Continuum Mechanics and with oil field simulators incorporating buoyancy as a hydrostatic mechanism and pressure gradients as driving forces. The oil industry is therefore not in the position to incorporate 'Buoyancy Reversal' in its mathematical models, meaning that mechanism is not taken into account within their elaborations.

Hubbert's Force Potential and the new concept of 'Buoyancy Reversal' should be applied to the study of carbon sequestration and the accumulation and production of hydrocarbons in order to improve the understanding of the physical processes involved. This will help to optimize both the methods of carbon sequestration and the recovery rate of hydrocarbons from reservoirs, and of unconventional gas plays.

Applying correct physics to the long-term migration of CO_2 by mathematical modeling of regional groundwater flow determines the eventual discharge points of injected CO_2, and the estimated time spans involved. The differences can be considerable as shown by the example of CO_2 sequestration at Weyburn by *Weyer* [2013]. If injection sites are properly selected, then these time spans will exceed thousands or tens of thousands of years before the CO_2 would enter surface water at regional discharge areas. Geochemical processes within regional groundwater flow systems will also significantly reduce the amount of CO_2 discharged at that time. These effects are created by the activity of groundwater flow systems.

References

Frind, E. O., and J. W. Molson, (2010)*, Review of "Physical Processes in Carbon Storage" by Udo Weyer, January 11, 2010, 16 pages

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, ARC Bull. No. 58., Edmonton, AB, Canada.

Hubbert, M. K. (1940), The theory of groundwater motion, Journal of Geology, 48 (8), 785-944.

Hubbert, M. K. (1953), Entrapment of petroleum under hydrodynamic conditions, AAPG Bulletin, 37(8), 1954-2026.

Weyer, K. U. (1978)*, Hydraulic forces in permeable media, Mémoires du B.R.G.M., (91), 285-297.

Weyer, K. U. (2010)*, Differing physical processes in off-shore and on-shore CO_2 sequestration, paper presented at GHGT-10, Amsterdam, The Netherlands.

Weyer, K. U. (2013). Regional groundwater flow pattern in the Northern Great Plains area and their effect on CO_2 sequestration at Weyburn, Saskatchewan, Canada. Proc. Symp. WRI-14, Avignon, France, June 2013.

* denotes papers available for download from http://www.wda-consultants.com

Post-proceedings comment: When submitting the paper, we inadvertently failed to change the term "Continuum Mechanics" to "Engineering Continuum Mechanics (Engineering Hydraulics)" as compared to the Continuum Mechanics system applied by Hubbert's (1940) with Force Potentials.

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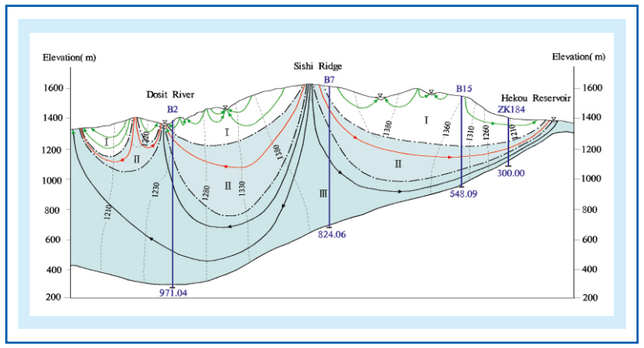

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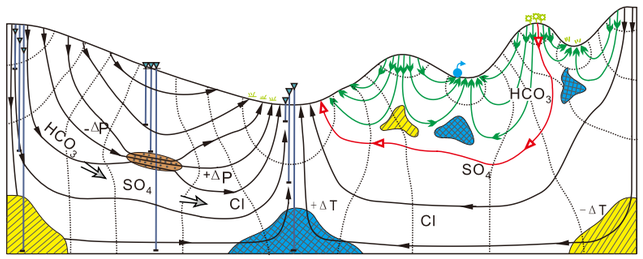

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