# Physics of Buoyancy, Pressure Potential and Buoyancy Reversal for $CO_2$ and Hydrocarbon Migration

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## Introduction

Traditionally pressure gradients and buoyancy forces play a central role in considering 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. The methodology shown applies to both $CO_2$ sequestration and hydrocarbon accumulations. Its consequences are shown on the $CO_2$ sequestration as an example.

Buoyancy forces are usually assumed to be directed vertically upwards, and its force is determined by density difference. Of great importance for successful $CO_2$ sequestration is the way we deal with so-called 'buoyancy forces' conceptually and within computer simulations. The general assumption is that fluids lighter than water (such as hydrocarbons and $CO_2$) will rise vertically upwards and fluids heavier than water will sink to the bottom of the geologic layer packet. These opinions are based on the assumption of hydrostatic conditions at sequestration sites. In reality the on-shore subsurface condition is one of flowing fluids under hydrodynamic conditions. In off-shore cases, hydrostatic conditions prevail (Weyer, 2010).

## Application of Hubbert's Force Potential

Hubbert (1953) showed the basic difference between hydrostatic conditions (Figure 1) and hydrodynamic ones. 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 (E in Hubbert's terminology; '–grad Φ' in this paper's terminology) is zero and no flow occurs. In the general hydrodynamic case the gravitational force and the pressure potential force do not assume opposite directions and equal magnitude. Therefore the resultant force vector is unequal to zero and flow occurs. In this case the 'buoyancy force' is not directed vertically upwards but can assume any direction in space including downward, as its direction follows the pressure potential force ($-1/\rho \bullet$ grad p).

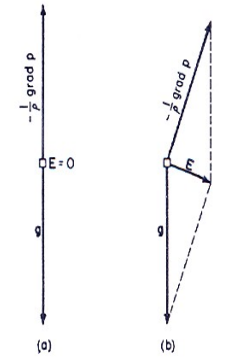

FIG. 4.—Physical interpretation of force-intensity vector **E**. (*a*) Hydrostatic case **E**=o; (*b*) hydrodynamic case.

Figure 1: Hydrostatic forces versus hydrodynamic forces (taken from Hubbert, 1953).

Please note that low velocities and/or low amounts of flow are irrelevant for the determination of hydrostatic conditions. The direction of the so-called ‘buoyancy force’ is determined by the force field, not by the flow field. In a low-permeable environment, at any point the flow of groundwater may be slow and of minor amounts, but the associated pressure potential forces will be high and will determine the ‘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).

Next we consider a hydrostatic condition with a freshwater body at the surface. Figure 2 schematically shows the different pressure potential gradients (forces) for salt water, fresh water, oil, and gas.

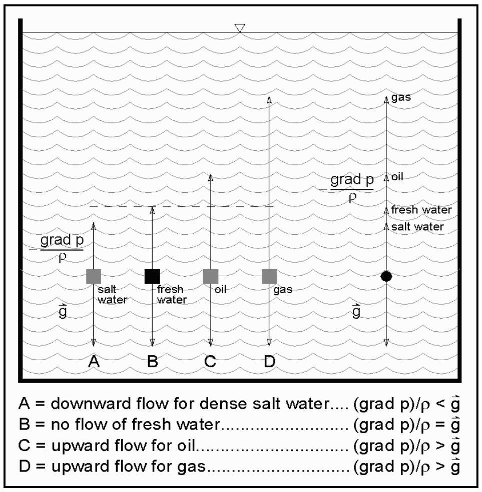

Figure 2: Schematic derivation of pressure potential forces (‘buoyancy forces’) for oil, gas, and salt water under hydrostatic conditions.

## ‘Buoyancy’ under Hydrostatic Conditions

The combined force vectors on the right side of Figure 2 amalgamate the pressure potential forces of fresh water, salt water, oil, and gas. They are all directed vertically-upwards because the fresh water pressure potential force potential force is directed vertically-upwards. The direction of the fresh water pressure potential force determines the direction of the pressure potential forces for oil, gas and salt water. That is the reason why oil and gas float vertically-upwards and saltwater vertically-downward **under hydrostatic conditions**.

## ‘Buoyancy’ under Hydrodynamic Conditions

Exactly the same happens under hydrodynamic flow conditions, except that the direction of the fresh water pressure potential force usually takes an oblique, non-vertical direction in space (Figure 3). This key to comprehending the behaviour of so-called ‘buoyancy forces’ which are actually pressure potential forces.

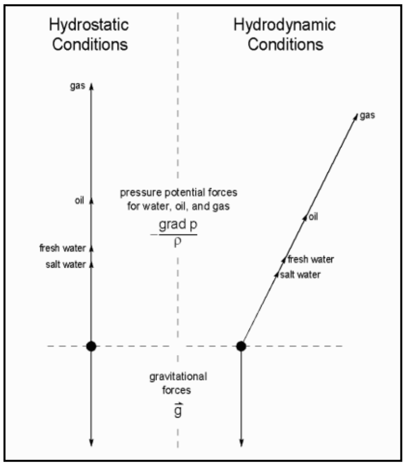

Figure 3: Comparison of the direction of pressure potential forces (so-called ‘buoyancy forces’) under hydrostatic and hydrodynamic conditions

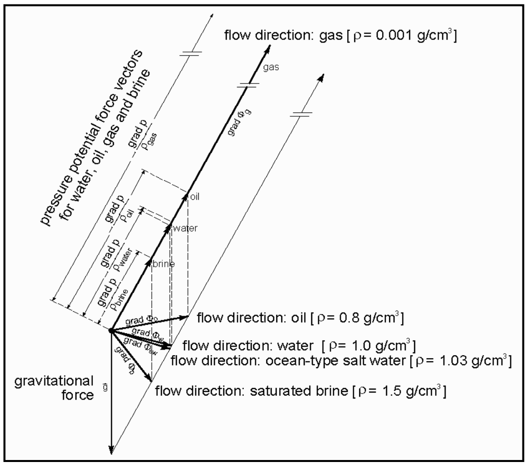

Figure 4: Determination of differing flow directions for fresh water, ocean-type salt water, saturated brine, oil, and gas within the same fresh water force field (schematic diagram modified from Hubbert, 1953). The flow direction of supercritical $CO_2$ would be similar to that of oil, according to its density.

Figure 4 shows the differing flow directions of various fluids within the 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.

## Buoyancy Reversal

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 7). The conditions occur when energy has to be taken from the compressed fluid element (groundwater) to maintain the amount of flow through low permeable layers such as aquitards and caprocks, thus causing reductions in pressure.

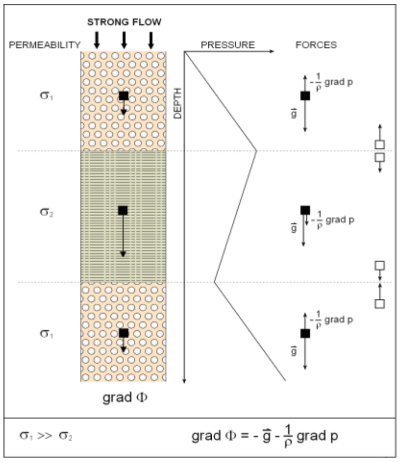

Figure 5: Distribution of forces at 'Buoyancy Reversal'

grad Φ = hydraulic force
$-\vec{g}$ = gravitational force
$-1/\rho \cdot$ grad p = pressure potential force

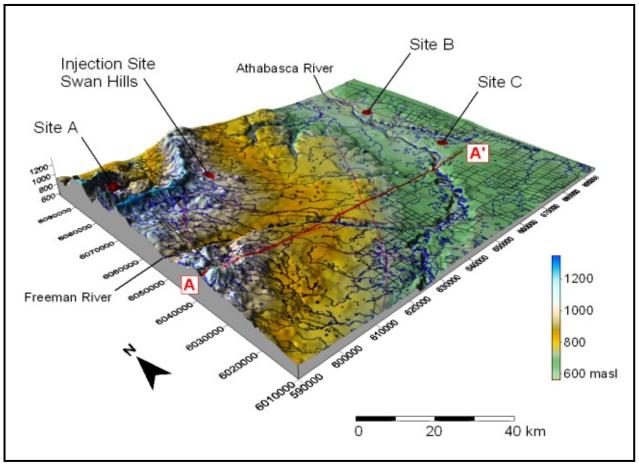

Figure 6: Digital Elevation Model [DEM] of the Swan Hills area. The geologic cross-section A-A' (in Fig. 10) is marked as a red line. At the sites A, B, and C the occurrence of Buoyancy Reversal was measured within the Clearwater-Wilrich aquitard.

Hitchon et al. (1989) described those conditions for the Clearwater-Wilrich Aquitard in the Swan Hills region of Alberta, Canada (Figures 8, 9). Figure 10 shows the sequence of layers containing the Clearwater-Wilrich Aquitard with high-permeable layers below this particular aquitard. The occurrence of layers with Buoyancy Reversal is widespread and well-known within the oil industry, but explained differently.

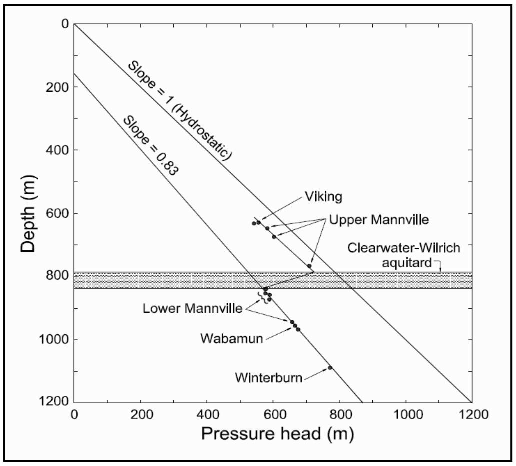

Figure 7: Buoyancy Reversal at Site C within the Clearwater-Wilrich Aquitard (after Hitchon et al, 1989).

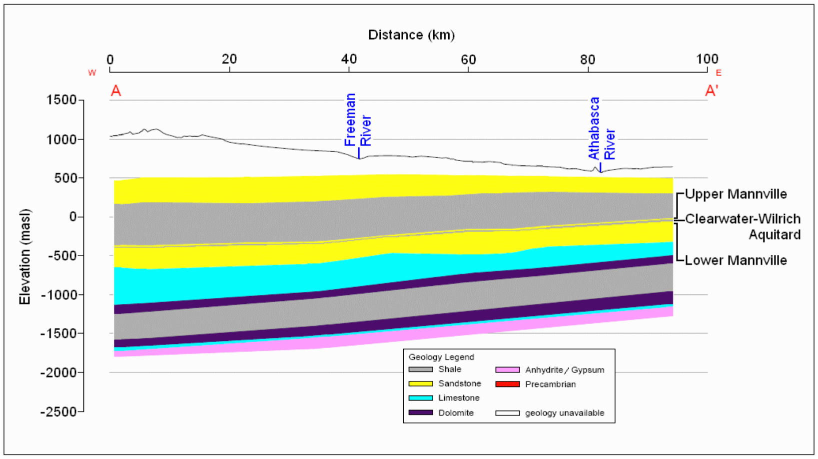

Figure 8: Geologic cross-section A-A'. See Figure 8 for location of cross-section.

Mathematically, the occurrence of Buoyancy Reversal has been modelled by Frind & Molson (2010). Buoyancy reversal occurs under recharge areas, while overpressure occurs under discharge areas as shown by the pressure-head profiles (Figure 9). It is remakable that in both cases the drop of pressure within the aquitard (caprock) is not an indicator of any barrier function within the aquitard (caprock). The 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.

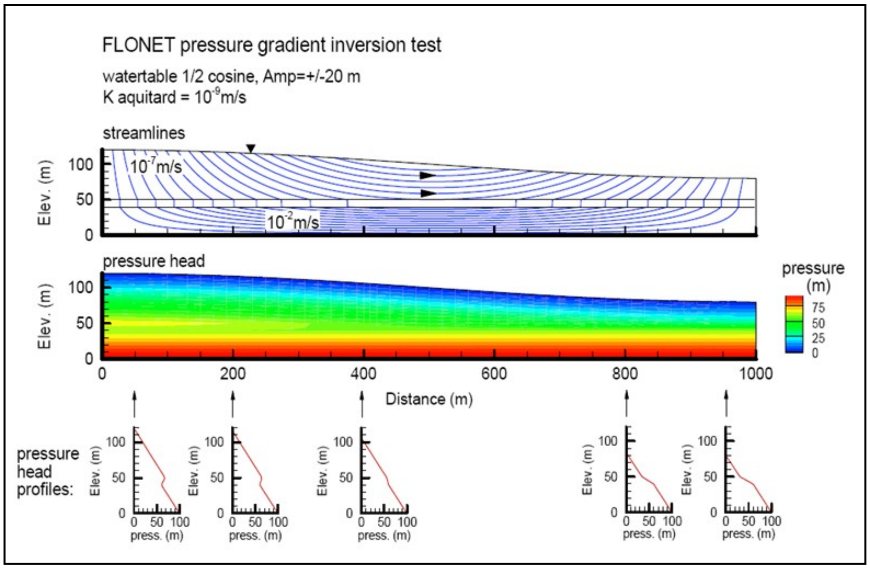

Figure 9: Natural groundwater flow system penetrating an aquitard creating pressure reduction in the aquitard and thereby buoyancy reversal under the recharge area with downward flow and overpressure under the discharge area with upward flow. In the past these conditions have often been misinterpreted in a non-physical manner. (Figure taken from Frind & Molson, 2010.)

## Conclusions

The existence of Buoyancy Reversal has been proven by theoretical derivation, field evidence, and mathematical modelling. There is now a pressing need to apply Hubbert's Force Potential and Buoyancy Reversal to the study of carbon sequestration and the accumulation and production of hydrocarbons in order to improve the understanding of the physical processes involved and to optimize both the methods of carbon sequestration and the recovery rate of hydrocarbons from reservoirs, and of unconventional gas plays, such as CBM and shale gas.

Applying correct physics to the long-term migration of $CO_2$ via existing models of regional groundwater flow determines the eventual discharge points of injected $CO_2$, and the estimated time span involved. If the injection sites are properly selected, then these time spans will exceed thousands or tens of thousands of years before the $CO_2$ would re-enter the atmosphere. Geochemical processes will also significantly reduce the amount of $CO_2$ discharged at that time.

## References

E.O.Frind and J.W.Molson, 2010. Review of "Physical Processes in Carbon Storage" by Udo Weyer. January 11, 2010. 16 pages [available from http://www.wda-consultants.com].

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.

Weyer, K.U., 1978. Hydraulic forces in permeable media. Mémoires du B.R.G.M., vol. 91, p.285-297, Orléans, France [available from http://www.wda-consultants.com].

Weyer, K.U., 2010. Differing physical processes in off-shore and on-shore $CO_2$ storage. Presented as poster at GHGT-10, Amsterdam, 2010. Published as private publication on the internet [available from http://www.wda-consultants.com].

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