Buoyancy, Pressure Potential and Buoyancy Reversal

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Introduction

Buoyancy plays a central role in carbon sequestration, be it in the determination of flow directions, or the determination of the height of breakthrough columns for CO_2. Usually it is assumed to be directed vertically upwards, and its force is determined by density difference. Of utmost importance for successful CO_2 sequestration is the way we deal with so-called 'buoyancy forces' conceptually and within computer simulation programs.

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 (no-flow conditions) at sequestration sites. In reality the subsurface condition is one of flowing fluids under hydrodynamic conditions.

Hubbert (1953) showed the basic difference between hydrostatic conditions (Fig. 1 below) 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; '$-\text{grad}\ \Phi$' in this poster'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 ($-1/\rho \cdot \text{grad}\ p$).

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. Fig. 2 schematically shows the different pressure potential gradients (forces) for salt water, fresh water, oil, and gas.

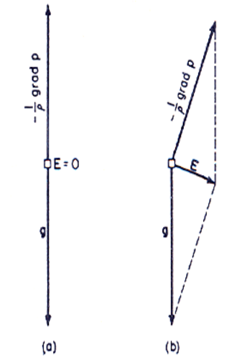

FIG. 4.—Physical interpretation of force-intensity vector **E**. (*a*) Hydrostatic case **E**=o; (*b*) hydrodynamic case.

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

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‘Buoyancy’ under Hydrostatic Conditions

The combined force vectors on the right side of Fig. 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 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**.

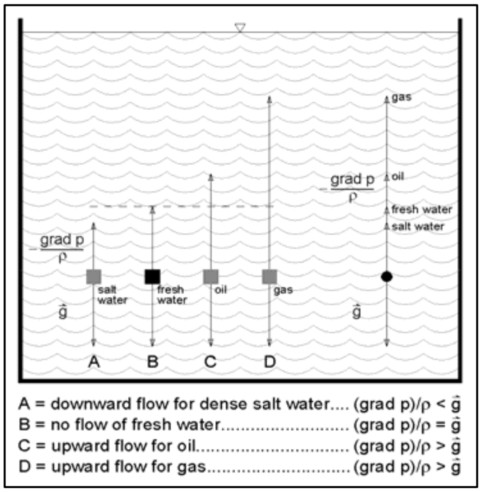

Fig. 2 Schematic derivation of pressure potential forces (‘buoyancy forces’) for oil, gas, and salt water under hydrostatic conditions

‘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 (Fig. 3). This is the key observation for comprehending the behaviour of so-called ‘buoyancy forces’ which are actually the pressure potential forces.

Fig. 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.

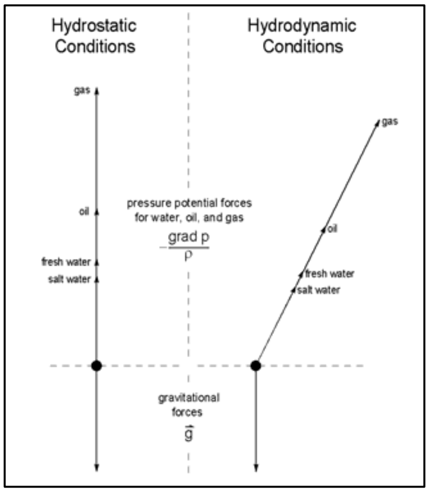

Fig. 3 Comparison of the direction of pressure potential forces (so-called ‘buoyancy forces’) under hydrostatic and hydrodynamic conditions

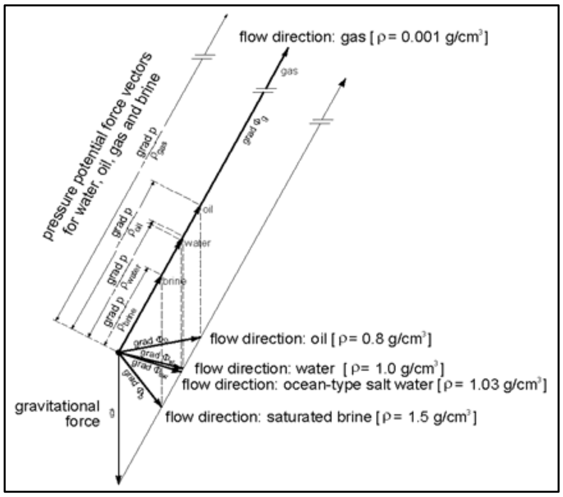

Fig. 4 Determination of differing flow directions for fresh water, ocean-type salt water, saturated brine, oil, and gas within the same fresh water force field (schematic diagram modified from Hubbert, 1953: Entrapment of Petroleum Under Hydrodynamic Conditions). The flow direction of supercritical CO_2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

The following photographs show upward-flowing salt water (Fig. 5) and saturated brine (Fig. 6) demonstrating that denser fluids can discharge at the surface.

Fig. 5 Discharging salt water from open borehole on south shore of Great Slave Lake, NWT, Canada (picture: Weyer, 1977)

Fig. 6 Upward discharge of saturated brine near Ft. Smith, NWT, Canada (picture: Weyer, 1977)

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 (Fig. 7). The conditions occur when energy has to be taken from the compressed fluid element (groundwater) to maintain the amount of flow, thus causing reductions in pressure.

Hitchon et al. (1989) described those conditions for the Clearwater-Wilrich Aquitard in the Swan Hills region of Alberta, Canada (Fig. 8, 9). Fig. 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.

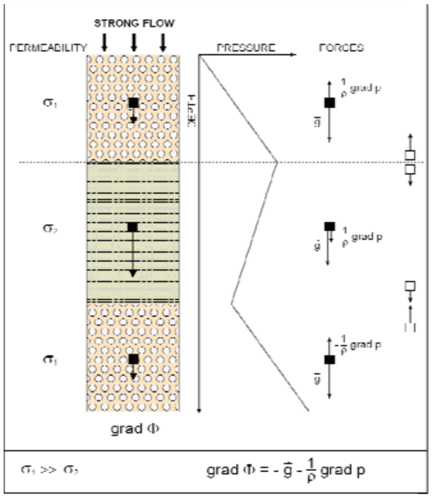

Fig. 7 Distribution of forces at 'Buoyancy Reversal'

grad Φ = hydraulic force

$-\vec{g}$ = gravitational force

$-1/\rho \cdot \text{grad}\ p$ = pressure potential force

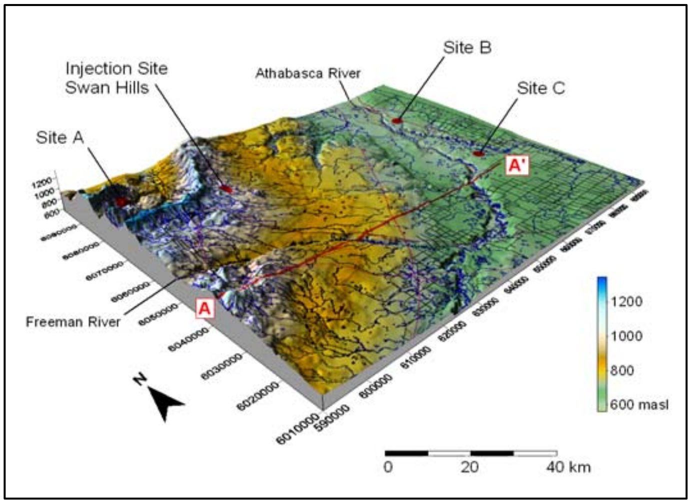

Fig. 8 Digital Elevation Model [DEM] of the Swan Hills area. The geologic cross-section A-A' (in Fig. 10) is marked as a red line. At the sites A, B, and C the occurrence of Buoyancy Reversal was measured within the Clearwater-Wilrich aquitard.

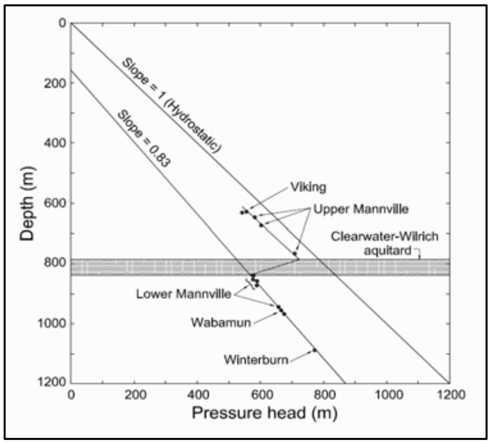

Fig. 9 Buoyancy Reversal at Site C within the Clearwater-Wilrich Aquitard (after Hitchon et al, 1989).

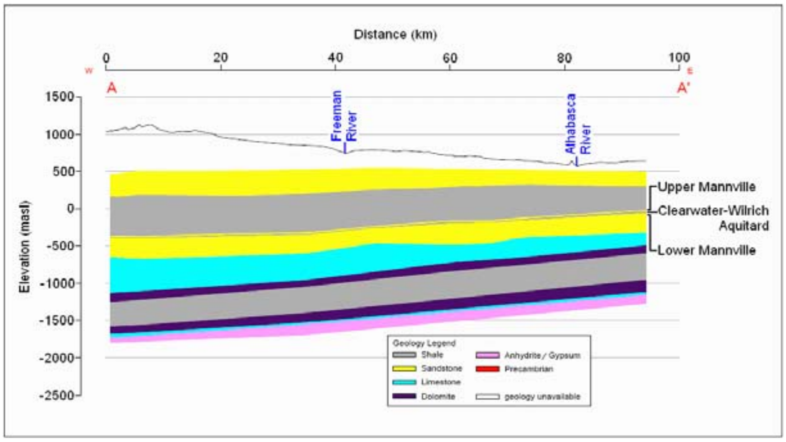

Fig. 10 Geologic cross-section A-A'. See Fig. 8 for location of cross-section.

Application of Pressure Potential Forces and Buoyancy Forces to CCS

- Non-vertical pressure potential forces may allow additional column length with respect to CCS breakthrough of aquitards.

- Layers with Buoyancy Reversal are an additional defence line against leakage of CO_2. While capillary forces are limited to the border between high- and low-permeable layers, the defence by Buoyancy Reversal is present throughout the low-permeable layer.

References

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.

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