Basic Physics of Geological Carbon Storage

K. Udo Weyer, Ph.D., P.Geol., P.HG.

WDA Consultants Inc., Calgary, AB, Canada / WKC Weyer Consultants, Krefeld, Germany

[weyer@wda-consultants.com]

Introduction

Hubbert, 1953, p.1960 showed that the force potentials (energy / unit mass) of fresh groundwater and the derived force fields determine the subsurface flow behaviours of other fluids in the subsurface such as salt water, oil or gas (including CO_2 in liquid or gaseous form). That is the reason why the force fields of groundwater flow systems have a direct effect upon the migration behaviour of sequestered CO_2. The basic equations for the mechanical groundwater force fields are:

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

Adding the mechanical capillary forces (in this case for CO_2) expands the equation to:

$$-grad\ \Phi_{CO_2} = \vec{g} - \frac{grad\ P}{\rho_{CO_2}} - \frac{grad\ P_c}{\rho_{CO_2}}$$

fluid force; gravitational force; pressure potential force; capillary force

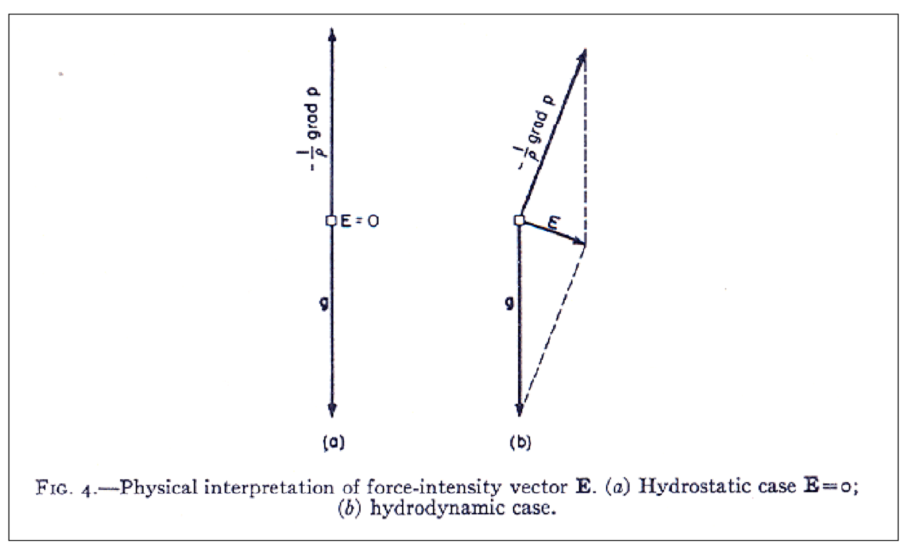
This poster concentrates, however, on non-capillary forces. Capillary forces occur only at borders between high- and low-permeable layers, while the other mechanical forces exist throughout the subsurface, including reservoirs, aquitards, caprocks, and saline aquifers. Therein lies the reason why groundwater force fields occur everywhere in the subsurface and flow systems are regional and continuous.

'Buoyancy forces' under Hydrostatic and Hydrodynamic Conditions

'Buoyancy forces' play a central role in the modelling of carbon sequestration, be it in the currently-applied methods to determine flow directions, or to determine the height of breakthrough columns for CO_2. Usually 'buoyancy forces' are assumed to be directed vertically upwards or downwards, and their magnitudes are determined by density differences.

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 all sequestration sites. In reality, onshore sequestration sites (i.e. Weyburn, Ketzin, etc.) have fluids flowing under hydrodynamic conditions. Offshore injection sites (Sleipner, Snøhvit, etc.) are subject to hydrostatic conditions. Offshore sites close to shore may be subject to either condition.

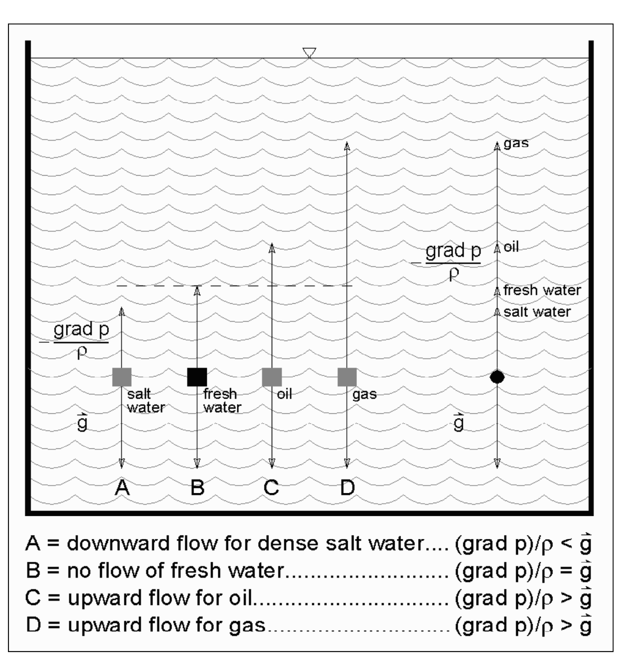
Hubbert (1953) showed the basic difference between hydrostatic conditions and hydrodynamic ones (Fig. 1). In the hydrostatic case the gravitational force and the pressure potential force are of exactly the same magnitude but pointing in opposite directions. The resultant force (E in Hubbert's terminology; '–grad Φ' 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 that of the pressure potential force (-1/ρ · grad p). In fact, the so-called 'buoyancy force' is the pressure potential force for the density of the fluid considered.



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 direction of 'buoyancy forces'.

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

'Buoyancy forces' under Hydrostatic Conditions



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

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 forces' under Hydrodynamic Conditions

The above principles also apply 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' under hydrodynamic conditions.

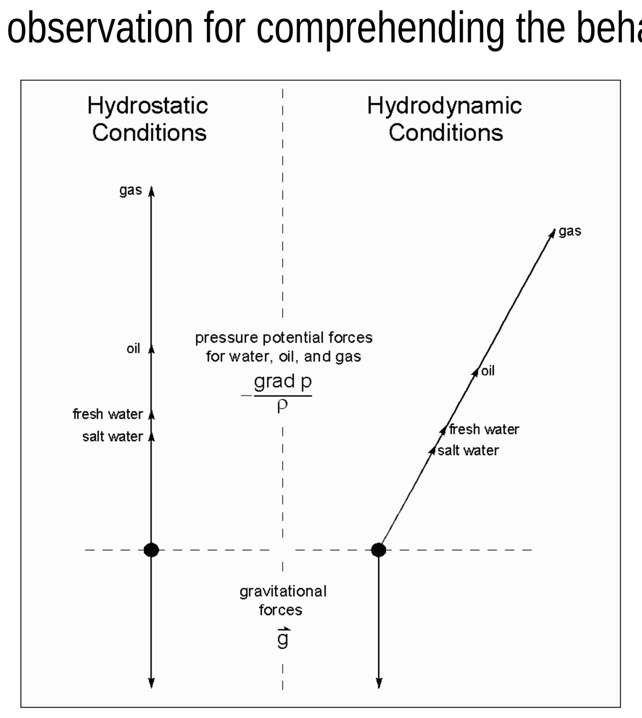


Fig. 3 Comparison of the direction of pressure potential forces (so-called 'buoyancy forces') under hydrostatic and hydrodynamic conditions

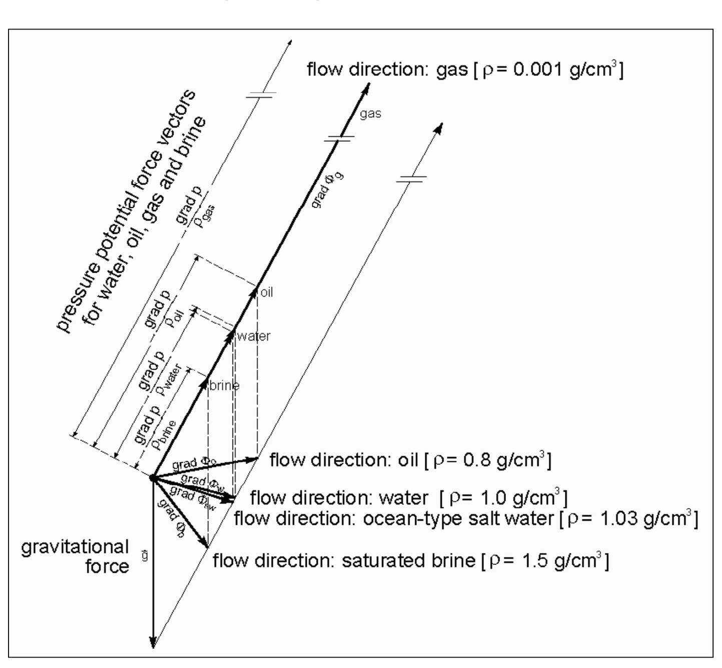


Fig. 4 Determination of differing flow directions for fresh water, ocean-type salt water, saturated brine, oil, and gas within the same fresh water force field (schematic diagram modified from Hubbert, 1953) The flow direction of supercritical CO_2 would be similar to that of oil, according to its density.

Fig. 4 shows the differing flow directions of various fluids within the fresh groundwater force field, as determined by vectoral addition. The different grad Φ directions indicate the different flow directions for fluids with different density in the same fresh groundwater force field. As a consequence, the so-called vertically-upward (density ρ < 1 g/cm³) and downward (ρ > 1 g/cm³) directed 'buoyancy forces' do not exist under hydrodynamic conditions.

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

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

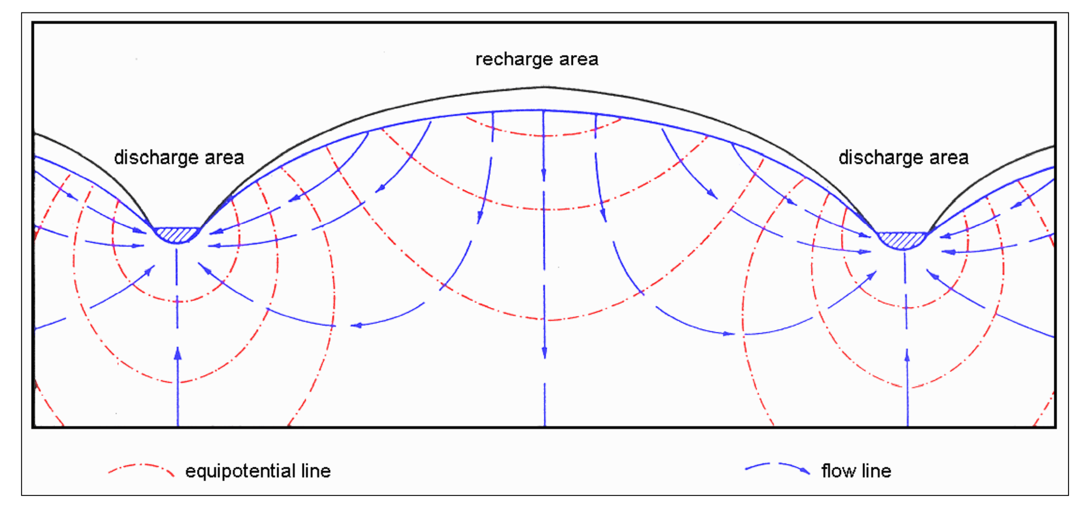
Fig. 6 Upward discharge of saturated brine near Ft. Smith, NWT, Canada (picture: Weyer, 1977)

Gravitational Groundwater Flow Systems

The Theory of Groundwater Flow Systems (Tóth, 1962) originated in Alberta, Canada in response to early cable tool drilling data from oil wells in the Turner Valley, 50 km southwest of Calgary, Alberta.

In the 1920s drilling was done with cable tool rigs without fluid circulation, while almost all other drilling methods used since apply mud or air circulation. The cable tool rig allowed a constant observation of the behaviour of the water level in the borehole with increasing drilling depth. Drilling on hills encountered water levels that decreased with depth once the groundwater table had been reached. In valleys the water levels rose with drilling depth and turned artesian (flowing). At the shoulder of valleys the water level did not change substantially. This behaviour was puzzling but was finally explained in the 1960s by applying Hubbert's (1940) Force Potential, which up to this time had been widely considered as an absurd opinion within hydrogeology. Thus Hubbert's theoretical development and analytical model of flow within a vertical cross-section (Fig. 7) was confirmed by actual field measurements in the Turner Valley oilfield.

Fig. 7 Energy fields (equipotential lines) and flow field (flow lines) of groundwater flow through homogeneous and isotropic rock in a cross-section between two valleys (after Hubbert, 1940, Fig. 45)



In Fig. 7, recharge areas occur in the elevated portion of the cross-section and discharge areas in the lowlands (valleys). The vertical flow lines under the top of the recharge area and in the middle of the discharge areas indicate hydraulic boundaries between flow systems. In undisturbed conditions, water does not penetrate from one flow system to another.

In an attempt to explain additional hydrogeological field evidence, simplified analytical calculations in topographical 2D vertical cross-sections led to the formulation of the principles of Groundwater Flow Systems (Tóth, 1962).

To further understand groundwater flow pattern, Freeze and Witherspoon (1967) determined the effect of topography and geologic structures of differing permeabilities upon groundwater flow pattern by simulating groundwater flow systems in 2D-vertical geologic cross-sections using early numerical computer models (Fig. 8).

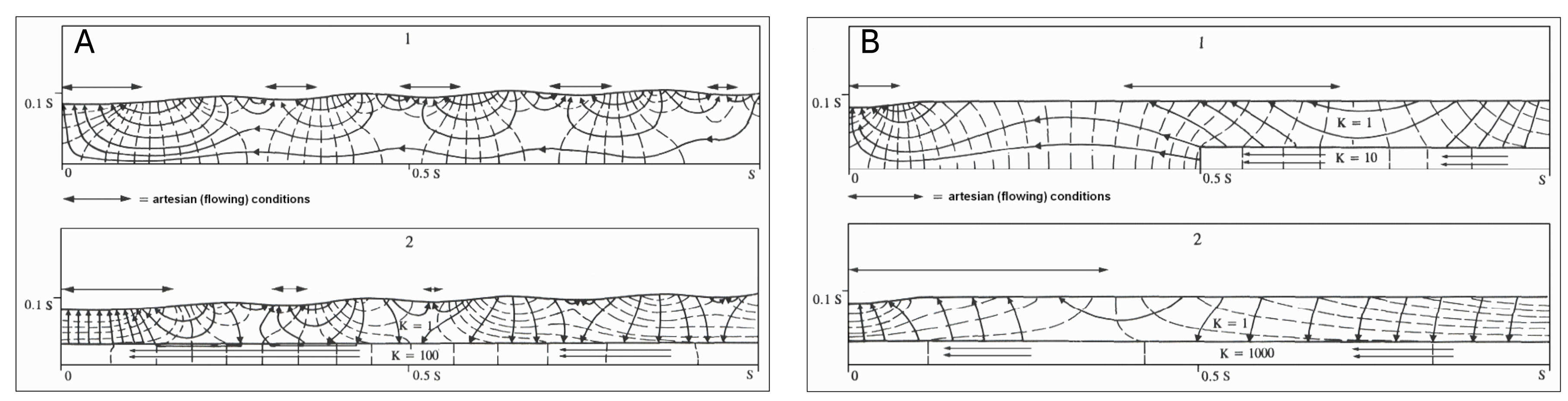


Fig.8 2D Mathematical models of geological cross-sections by Freeze and Witherspoon [1967]: Effect of a buried higher-permeable layer [1,2] upon groundwater flow pattern and location of recharge and discharge areas.

Fig. 9 Schematics of groundwater flow patterns for common types of regional landforms: (b) intracratonic basin with broad uplands; (d) cordillera-cum-foreland. The schematic topography in case (d) is similar to the situation in Alberta, Canada. All cross-sections are devoid of heterogeneities. The cross-sections have been selected from Tóth (2009), Fig. 3.14.

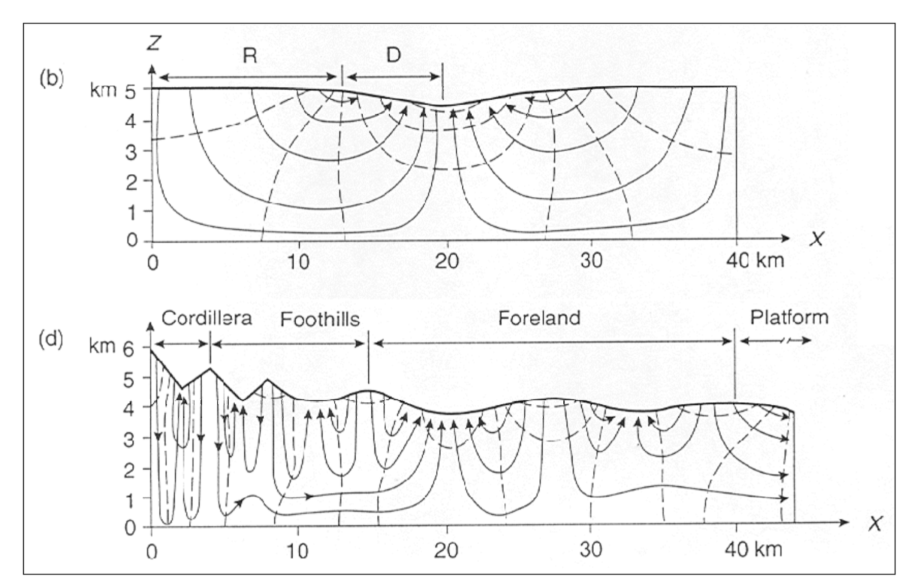


Fig. 8 illuminates the effect of permeable deep geologic layers under aquitards on groundwater flow. In Fig. 8 [B2], the overlying aquitard (caprock) is penetrated twice (downward and upward) and therefore, in this case, twice as much groundwater flows through the aquitard as compared to the deep aquifer. Fig. 9 shows groundwater flow penetrating to a depth of more than 5 km, well into and through planned storage sites for CO_2 injections. Hence, regional gravitational groundwater flow will determine the long-term migration pattern of injected CO_2.

More detailed information on all the above subjects is contained in Weyer, 2010 which can be downloaded from http://www.wda-consultants.com.

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