Free convection or variable density flow within groundwater flow systems?

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Introduction

In northeastern Alberta, free convection has been postulated by Bachu et al. (1993) and Bachu and Underschultz (1993) disguised as buoyancy-driven downdip flow in deep aquifers opposing gravitationally-driven updip flow within groundwater flow systems. This postulate is based on the assumption that the buoyancy of heavier fluids is directed vertically downward and then obliquely reflected downdip within the bottom part of dipping aquifers on top of underlying aquitards. At first glance this concept seems to be reasonable and could thereby be handily applied to determine the fate of saline water as subject to downdip flow directions, while lighter fluids such as hydrocarbons or sequestered CO_2 would be subject to buoyancy-driven updip flow moving along the upper parts of aquifers underneath an overlying aquitard.

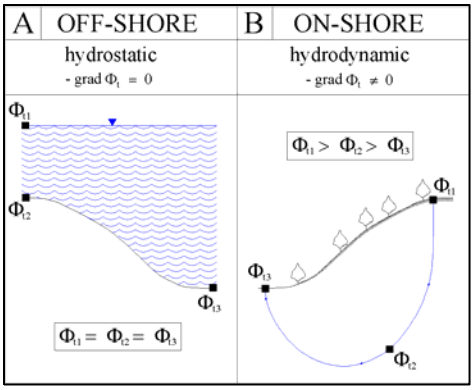
Theory

Buoyancy-driven downdip flow of saline water and updip flow of lighter material exists under hydrostatic conditions in resting water bodies as represented by the conditions (A) in Figures 1, 2, and 3. In these water bodies, gravitational force vectors $\vec{g}$ and the pressure potential forces vector -(1/ρ) grad p have the same magnitude but opposite directions (Figure 2A). Hence no gravitationally-driven flow occurs. The calculation of pressure potential forces for fluids with lower densities than the host fluid increases the pressure potential force for the lighter fluid and, as a consequence the resultant force is directed vertically upwards and the lighter material moves accordingly. The calculation of pressure potential forces for fluids heavier than the host fluid leads to a pressure potential vector smaller than $\vec{g}$ and thus the heavier fluid moves vertically downwards.

While gravitationally-driven flow does not exist under hydrostatic subsurface conditions off-shore, it exists under the hydrodynamic conditions (B) on-shore as shown in Figures 1, 2, and 3. The host fluid is not at rest but flows driven by unbalanced gravitational and pressure potential force fields. These force fields are created in response to the upper boundary conditions of the fresh groundwater body, the groundwater table. All other fluids are subject to the fresh water pressure potential force field (Hubbert, 1940, 1953).

All density-related modifications of pressure potential forces are calculated along and in the direction of the fresh water pressure potential vector. Vectorial addition then follows the procedures schematically outlined in Figure 4.

The resultant calculation leads to different flow directions for the various fluids of differing density (compare Figure 4). Thus ocean-type salt water (ρ = 1.03 g/cm^3) has nearly the same flow direction as fresh water, saturated brine (ρ = 1.3 g/cm^3) flows under the depicted situation downward in an oblique direction, whilst oil and CO_2 (density ρ ~ 0.8 g/cm^3) would flow upwards in an oblique direction, determined by the fresh water force field.



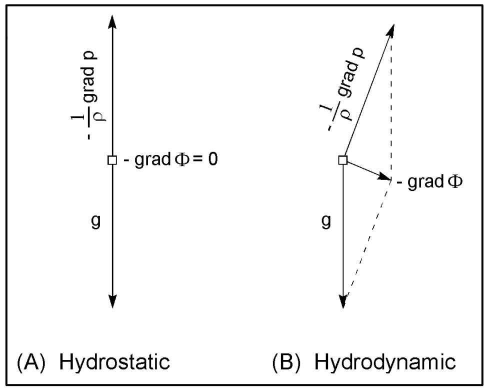
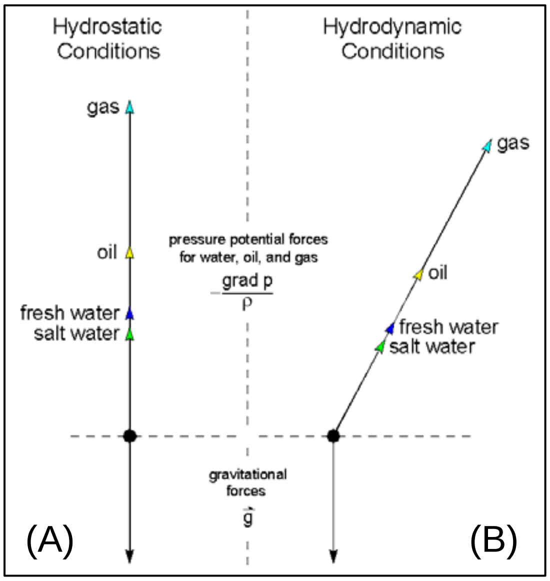


Figure 1 (left): *Comparison of hydrostatic and hydrodynamic conditions in subsurface fluid flow (from Weyer, 2010). [Φ: hydraulic potential; grad Φ : hydraulic force]*

Figure 2 (right): *Hydrostatic forces versus hydrodynamic forces (after Hubbert, 1953).*



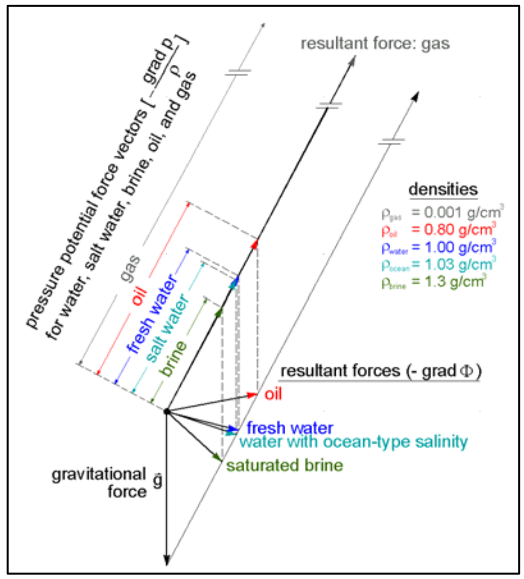
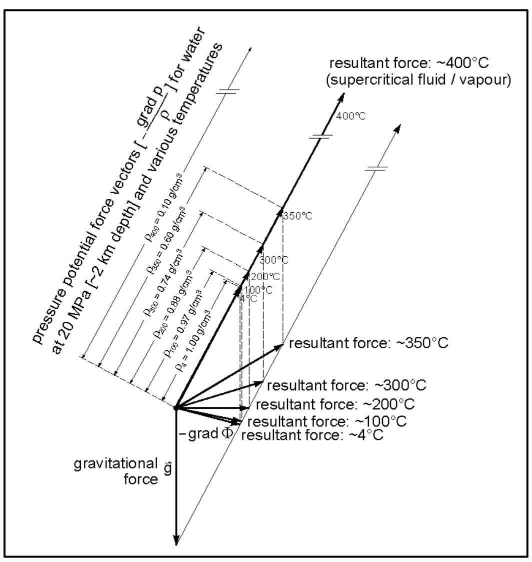


Figure 3 (left): *Comparison of forces under hydrostatic and hydrodynamic conditions (from Weyer, 2010).*

Figure 4 (right): *Resultant calculation of flow directions for fluids of different density within the fresh water force field. From Weyer (2010).*



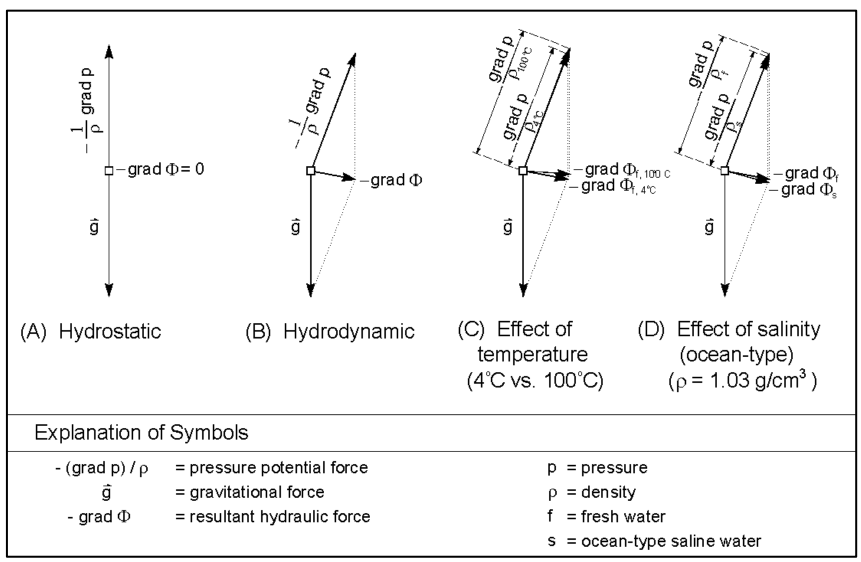


Figure 5 (left): *Resultant calculation of flow directions for water of different temperatures (density) at 20 MPa within the fresh water force field.*

Figure 6 (right): *Comparison of resultant force calculations for water under (a) hydrostatic conditions, (b-d) hydrodynamic conditions, (c) with variable temperatures, and (d) variable salinity. From Weyer & Ellis (2015).*

It is important to point out that hydrostatic conditions, the conditions of no flow, are a special case of hydrodynamic conditions. Under both conditions the density modification is calculated along the direction of the pressure potential force. In nature, hydrostatic conditions prevail under oceans (Figure 1A), hydrodynamic conditions in the subsurface of landmasses (Figure 1B).

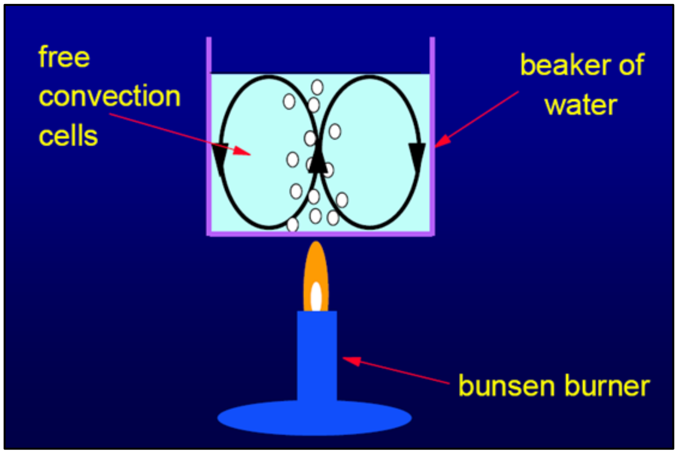
Contrary to widespread opinion, there exists no convection cells under hydrodynamic conditions. Instead, resultant forces for different temperatures are calculated as shown in Figure 5. Figure 6 compares the calculation of hydrostatic resultant forces, with hydrodynamic resultant forces under the conditions of varying temperature and salinity. The ruling physical conditions have been summarized by Hubbert (1940, 1953). The mathematical treatments by Muskat (1937), Bear (1972) and de Marsily (1986) are physically incorrect.

Free Convection

Bear (1972, p. 642) defined convection as follows: "*Convection imposed by internal means is known as forced convection, while fluid motion caused by density differences due to temperature variations in the field of flow is called free, or natural convection.*"

While Bear (1972) related free convection to heat from inside a flow field, Simmons (2011) related it, in a laboratory setting, to heat added from outside the flow field (Figure 7) and Van Dam et al. (2009) see free convection as a density dependant flow driven by heavier fluids above lighter fluids causing fingering (Figure 8). The examples in Figure 7 and 8 relate to hydrostatic conditions, not to on-shore hydrodynamic field conditions. That was noted by Simmons (2011) when he stated "*Hundreds of papers on theory, modelling & laboratory experiments on finger instabilities associated with free convection… **BUT A COMPLETE LACK OF CONCLUSIVE FIELD BASED EVIDENCE AND DATA!***" (emphasis by Simmons, 2011).

Van Dam et al. (2014) claim that fingering had now be shown to exist in the sabkha (Arabic: salt flat) areas of Abu Dhabi, based on geophysical field data which had been taken in 2008 and 2009. They attempted to support their interpretation with a simple vertical 2D-mathematical model of 30 m width and 10 m depth with oversimplified boundary conditions and parameters representing an hydrostatic case in a closed box with no-flow boundaries at the two sites and at the bottom of the model.



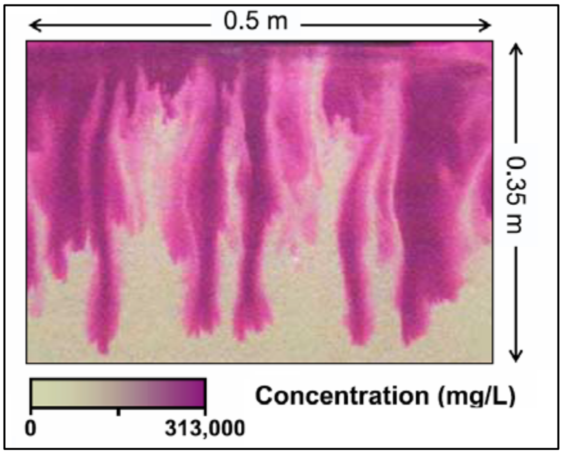


Figure 7 (left): *Simple explanation of free convection in a beaker above a source of heat (after Simmons, 2011).*

Figure 8 (right). *Representative examples of fingering associated with unstable free convection in groundwater from laboratory experiments. Figure from Van Dam et al. (2009). In the experiment a heavier saline fluid is positioned upon the less saline water under hydrostatic conditions.*

Abu Dhabi Sabkha Field Case

Van Dam et al.'s (2009, 2014) assumption has been that the Abu Dhabi field site (Figures 9 and 10) is regularly flooded by the sea water (ρ ~ 1.03 g/cm^3) of the Gulf which would create a natural condition of heavier saline water overlying less dense water. According to their concept, fingering would then occur as had been interpreted from electrical geophysical field data taken in 2008 and 2009. Figure 8 reports the results of laboratory tests with brines close to a density ρ ~ 1.3 g/cm^3 situated over fresh water. The situation at the Abu Dhabi field site is systematically different in that the sabkha areas are endpoints of regional groundwater flow systems discharging salty water, not fresh water, from greater depth (Wood et al., 2002). Therefore denser water would occur under less dense water, contradicting the assumption taken by Van Dam et al. (2009, 2014).

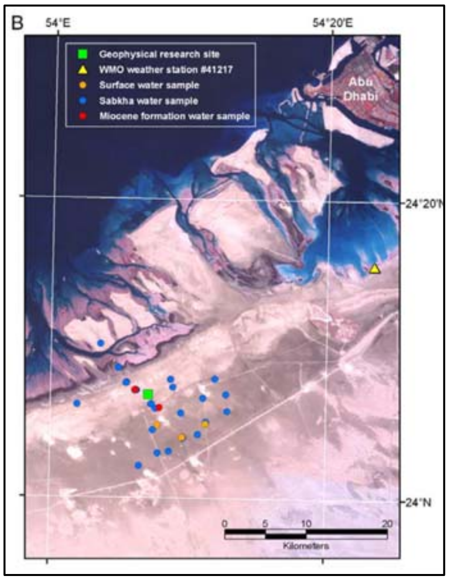


Figure 9 (left): *Figure from Van Dam et al. (2009, Fig 2c) showing the positioning of the geophysical research site and surrounding study points.*

Figure 10 (right): *DEM based on SRTM topographic data. The position of the Van Dam et al. (2009, 2014) geophysical research site is shown to be approximately 5 km from the coastline.*

During a strong rain event before the 2008 measurements local recharge of fresh water occurred at the little hills of the hummocky terrain shown in Figure 10 giving rise to small local groundwater flow systems, which led then to the presumed 'fingering' reported by Van Dam et al. (2009). The difference is that in this scenario, it is the fresher less dense water which penetrated into salty water driven by the force field of groundwater flow systems. That leaves open the question: where does the salty water below the penetrating fresher water come from?

Fortunately, the sabkha area of Abu Dhabi has been seen by sedimentologists of the petroleum industry as a natural present day laboratory to explain the huge amount of dolomitization which has occurred in the geological past. Several schools of thought were proposed to explain the migration of magnesium into the carbonates, such as the "seawater-flooding model" (Kinsman, 1969; Butler, 1969; Butler et al., 1973; Patterson and Kinsman, 1977, 1981, 1982) and the "evaporative-pumping model" (Hsü and Siegenthaler, 1969; Hsü and Schneider, 1973; McKenzie et al., 1980; Müller et al., 1990). None of the two schools concerned themselves with the actual physics of the flow processes they proposed. Wood et al. (2002) were the first authors conducting actual hydraulic field work in the Abu Dhabi sabkha area by drilling 450 shallow (<5 m), 21 intermediate depth (<15 m), and 6 deep (~100 m) piezometers as shown in Figure 11. All six deep piezometers were artesian, with flowing salty water. It was thereby established that the source of the magnesium, needed for dolomitization, was continental and not seawater. By establishing the sabkha region as a regional discharge area, Wood et al. (2002) also established that free convection was not operational at the Abu Dhabi sabkhas. Seemingly Van Dam et al. (2009, 2014) overlooked Wood et al.'s (2002) work whilst positioning their investigation site in the general area of Wood et al.'s (2002) deep flowing wells 291 and 306.

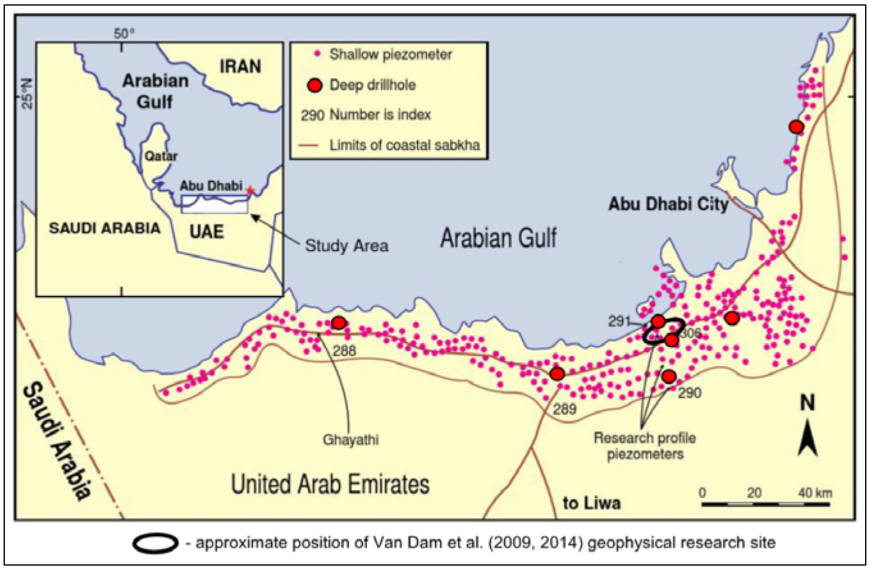


Figure 11: *Map showing the location of shallow, intermediate, and deep piezometers on the coastal sabkha of Abu Dhabi. Modified from Wood (2011), after Wood et al. (2002).*

Conclusions

Close physical analysis of free convection and the associated vertical buoyancy and density forces shows that they do not exist in a natural continental subsurface environment. All density and buoyancy derived forces need to be included by modifying the length of the pressure potential forces of fresh water force fields regardless if fresh water is present at that position following Hubbert's (1940, 1953) physical treatments. As a consequence, adjustments should be made in dealing with the migration of hydrocarbons and CO_2 as well as in regard to our understanding of present day and past geological processes as for example dolomitization. The chemical and hydrodynamic pattern at the Abu Dhabi sabkhas are determined by groundwater flow systems, not by free convection.

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