Successful Geologic CO_2 Storage by Geofluids System Analysis

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Abstract Hubbert's Force Potential and Groundwater Flow System Theory need to be applied to the geologic storage of CO_2, thus enabling the migration pathways, the end points of migration, and the approximate time span for the CO_2 migration to be calculated by appropriate methods. The methods of reservoir engineering suffice for the production of petroleum but should not be applied to geologic CO_2 storage.

Key Words CO_2 storage, CO_2 migration, groundwater flow systems, Hubbert's force potential, hydrodynamics

Introduction

The geologic storage of CO_2 demands a new type of subsurface fluid mechanics extending beyond that required for hydrocarbon production and application of EOR. Traditional subsurface fluid mechanics deals with hydrocarbon reservoirs primarily as sinks for flow of water, hydrocarbons and CO_2 or other EOR enhancers. CO_2 sequestration, however, leads us to deal with reservoirs and saline aquifers as sources for flow of CO_2 into the geological environment. In the past the question of physical causality of fluid mechanics was not one of importance as the fluids would enter the production wells in any case and the actual flow paths usually were not of great significance. What was important was the success in resource extraction and the ensuing and proven economic profitability. Thus traditional fluid mechanics was and is sufficient for successful resource extraction.

Geologic CO_2 storage, however, causes a paradigm shift in the sense that the application of fluid dynamics now must ensure as much storage volume as possible and needs to predict how much CO_2, after large scale injection, may return to the surface as well as the time scales and migration paths involved. These new goals, for the first time in its history, will require subsurface fluid mechanics to apply systems which are physically consistent and are based on the application of physical causality throughout. For example, it will not suffice to relate the energy to unit volume and to assume incompressibility of water or to assume hydrostatic conditions for the application of so-called buoyancy forces. All of this is done in continuum mechanics and the brand of thermodynamics derived from these assumptions. Instead subsurface fluid mechanics, adapted to CO_2 storage, will need to apply Hubbert's Force Potential (1940, 1953) which relates energy to mass and need not assume incompressibility or vertical buoyancy forces, as well as Groundwater Flow Systems Theory.

A generally held assumption is that the flow conditions at off-shore and on-shore CO_2 injection sites would be the same and sufficiently described by the application of so-called 'buoyancy forces' directed vertically upward for a fluid lighter than the prevailing fluid and vertically downward for a heavier fluid. As a matter of fact, the addition of CO_2 to water in saline aquifers has been described as 'a fail safe way to dispose of CO_2' as the dissolution of CO_2 will increase the density of the saline water and thereby cause density-driven downward flow which would ensure permanent safe storage at greater depth. Weyer (2010a) has shown this assumption to be incorrect by presenting several field examples documenting upward discharge of ocean-type salt water (density 1.03 g/cm^3) and even of saturated brine (density 1.3 g/cm^3) to the surface.

Hubbert (1940, 1953) established (Figure 1) that the so-called 'buoyancy forces' are pressure potential forces, which are directed vertically upwards under hydrostatic conditions (no gravitationally driven flow) but which, under hydrodynamic conditions (gravitationally driven flow), are directed in an oblique fashion. Within low permeable aquitards (caprocks), the pressure potential forces for lighter fluids may also be directed downwards (Weyer 1978: 'Buoyancy Reversal'). This paper explains the differences between hydrostatic and hydrodynamic conditions and shows why flow behaviour at the Sleipner site (off-shore, hydrostatic environment) is fundamentally different from the flow behaviour at the Weyburn site (on-shore, hydrodynamic environment). Hence the Sleipner site cannot be a test case for the hydrodynamics of on-shore storage of CO_2.

Hydrostatic versus Hydrodynamic Fluid Environment

Hubbert's force potential (energy/unit mass) is the sum of the gravitational energy Φ_g and the pressure potential energy Φ_p stored in and available from the unit mass of hydrous fluid ($\Phi = \Phi_g + \Phi_p$). The gradients of these energies are the vec-

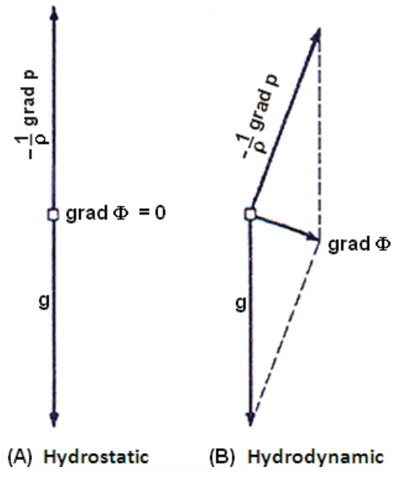

Figure 1 Hydrostatic forces versus hydrodynamic forces (after Hubbert 1953).

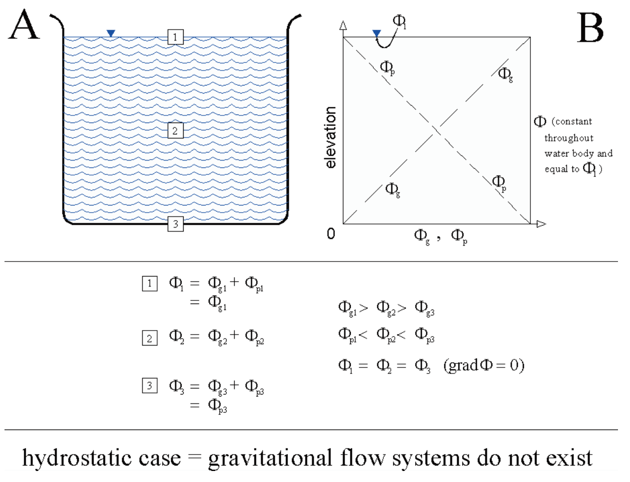

Figure 2 Hydrostatic conditions in a pail (from Weyer 2010a). The value of the fluid potential Φ is constant throughout the water body (part A). The gravitational potential Φ_g and the pressure potential Φ_p, however, change in synchronous opposition with depth (part B).

torial forces propelling subsurface fluid flow whereby g is the earth's acceleration, p is the pressure and ρ is the density of the fluid considered:

$- \text{grad}\ \Phi = g - (\text{grad}\ p) / \rho$.

The respective physics is explained by Hubbert (1940, 1953) and Weyer (1978). In this paper we will concentrate on the differences between hydrostatic and hydrodynamic energy conditions, as they determine the migration pattern of CO_2 stored within their realm.

Figure 2 outlines the energy distribution in a hydrostatic water body, say a pail of water, a lake, or the sea. The hydraulic potential Φ has the same magnitude at all positions within the water body ($\Phi_1 = \Phi_2 = \Phi_3$). Given a constant density throughout, this would hold true within any surface water body, and within subsurface water beneath the sea due to the same potential existing as a boundary condition at the bottom of the sea (Fig. 3A). The gravitational potential Φ_g and the pressure potential Φ_p are, however, conjoined (Fig. 2) such that their respective additions would always result in the magnitude of the total hydraulic potential Φ equaling that of the water surface, as described above.

As the hydraulic potential is the same anywhere within the hydrostatic water body, the hydraulic force grad Φ is zero within hydrostatic fields and no gravity-driven flow occurs. These conditions exist at all off-shore geologic storage sites wherein injection of CO_2 causes buoyancy-driven flow within a system without gravity-driven flow. This process has been well documented under the North Sea at the Sleipner site. Other off-shore sites with similar characteristics are Snøhvit in the North Sea off the coast of Norway, the Gorgon and Gippsland projects off the coast of Australia, and the Pre-Salt targets within the Santos Basin and Campos Basin in the Atlantic off the coast of Brazil. The Gippsland Basin and other coastal areas have an intervening area between the hydrostatic and hydrodynamic regimes wherein the hydrodynamic regime extends some, hitherto unknown, distance under the sea.

Figure 3 compares the flow conditions at off-shore sites (Figure 3A) with on-shore sites (Figure 3B). At off-shore sites, hydrostatic conditions exist, whilst at on-shore sites hydrodynamic conditions prevail. At on-shore sites, the energy conditions along the gravitational flow path are such that $\Phi_1 > \Phi_2 > \Phi_3$. Groundwater flow systems can reach from the groundwater table to depths of five kilometres or more depending on the topography of the groundwater table and the sequence of geological layers (see model results by Tóth 1962, 2009 and Freeze & Witherspoon 1967). Freeze and Witherspoon (1967) show that under natural conditions twice as much groundwater may flow through the overlying aquitard (caprock) downwards and upwards than laterally through the aquifer. The reasons for these conditions have been explained by Weyer (2010a, p.15, 16).

Effect of Gravitational Groundwater Flow Systems on On-Shore Storage

Hubbert (1953, p.1960) established that, on-shore, the force fields of fresh groundwater determine the migration behaviour for salt water, oil, natural

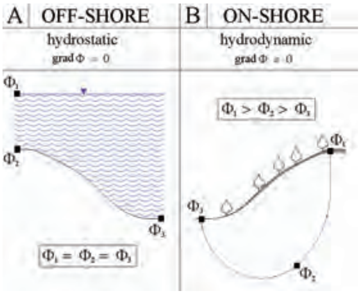

Figure 3 Comparison of hydrostatic and hydrodynamic conditions in subsurface fluid flow (from Weyer (2010a). [Φ: hydraulic potential; grad Φ: hydraulic force].

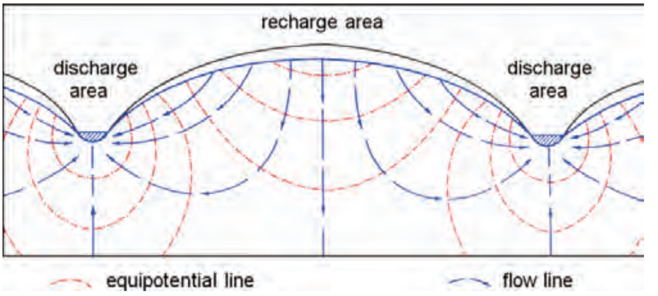

Figure 4 Energy fields (equipotential lines) and flow field (flow lines) of groundwater flow through homogeneous and isotropic rock in a cross-section between two valleys (after Hubbert 1940).

gas and, as we now know, also the long-term migration behaviour of injected CO_2. He also worked out that caprocks may be impermeable to the migration of hydrocarbon due to capillary effects but not to the migration of hydrous fluids in either direction. Hubbert's (1953) observations have severe consequences for the storage of CO_2 as, on-shore, the force fields of gravitational groundwater flow systems govern the long-term migration behaviour of CO_2 stored in deep geologic layers. The knowledge of the pattern of regional groundwater flow systems and their force fields allows the determination of the length of time until the stored CO_2 gradually discharges into water bodies at the surface. This time span may be thousands or tens of thousands of years if injection sites and target layers are properly selected according to the principles of gravitational groundwater flow.

For this purpose, factual and unbiased investigations of the dynamics of deep-seated groundwater flow systems need to be undertaken in the context of geological CO_2 storage. So far that does not seem to have been done at any of the onshore injection sites presently tested for future CO_2 storage. Figure 4 depicts the gravitational groundwater flow pattern determined by Hubbert (1940). Based on water level data in wells of the Turner Valley oil field southwest of Calgary a group of young engineering geologists developed the concept of groundwater flow systems which culminated in the publication by Tóth (1962). Since then groundwater flow systems have been studied and confirmed on all continents ranging in size from a few meters to many hundreds of kilometers.

Münchehagen case (Germany): The Münchehagen case is described in detail by Weyer and van Everdingen (1995) which due to space limitations should be downloaded from the WDA website. It deals with a groundwater flow system penetrating from a hill of less than 80 m height to a depth of about 1000 m (the bottom end of the model), picking up salt along the deep flow lines from salty marl and discharging ocean-type salt water back to the surface. A 2D freshwater model returned the flow paths for ocean-type saltwater in surprising detail which accurately reflected field observations. The Münchehagen case is one of several case histories of 2D-modeling, in geological cross-sections, regional groundwater flow systems in Europe undertaken by Weyer (1996).

Weyburn case (Saskatchewan, Canada): Figures 5 and 6 show the topography in the Weyburn area. The topographical (and thereby approximate groundwater table) elevation differences of more than 200 m between the hills (recharge areas) and valley of the Souris River are sufficient to maintain natural gravitational flow systems to the depth of the oil field and the present CO_2 - EOR operation.

Similar conditions exist at other test areas in Western Canada, such as Zama Lake, Heartland, Wabamun and others. Presently none of these sites have been investigated for the pattern of natural flow systems as they existed before the extraction of hydrocarbons. The methods for such investigations are available. Upon storage of CO_2, the slightly-modified natural groundwater flow systems will determine the migration pathways and delay time to discharge to the surface. These discharge areas are the valleys of rivers and lakes connected to deep-seated groundwater flow systems.

Green River case (Utah, USA): Figure 7 shows the natural discharge of CO_2 at the Green River in Utah from a deep-seated groundwater flow system in much the same manner as shown in Figure 8. In the model, the upward discharge from the deep flow system enters the river from beneath. A flowing borehole is positioned on the side of the simulated river which extends at the bottom into the deep groundwater flow system. At the Green

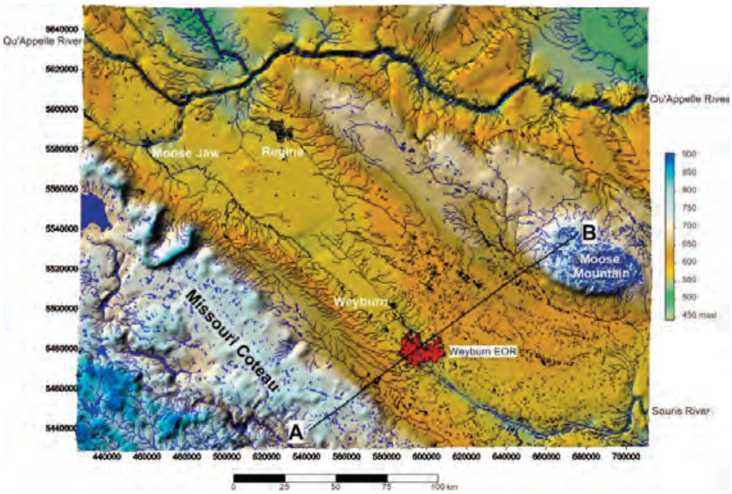

Figure 5 Bird's-eye view of the DEM for the general Weyburn area. Topographical cross-section A-B is shown in Figure 12 (from Weyer 2010a)

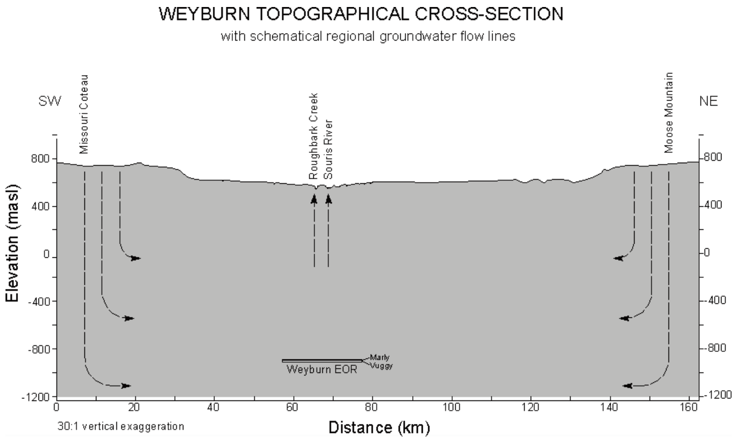

Figure 6 Topographical cross-section A-B from Missouri Coteau to Moose Mountain with elevation differences well in excess of 200 m. For location of cross-section, see Figure 5 (from Weyer 2010a).

Figure 7 Natural discharge of CO_2 at the Crystal Geyser on the bank of the Green River, Utah, as the end point of a large-scale regional groundwater flow system. (Weyer 2010b)

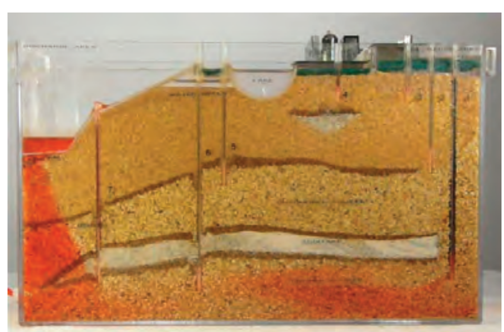

Figure 8 Demonstration of deep groundwater flow with dissolved CO_2 entering a surface water body from beneath in a table-sized sand model. (Weyer 2010b)

River, the discharge of CO_2 is not only manifested by artesian flow through an open exploration borehole (Figure 7) but also by carbonate precipitation into fractures within sandstone at the river bank. It is essential that detailed studies be done to explore the effects of groundwater flow systems upon the storage of CO_2 as outlined by a roadmap presented in Weyer (2010a). CO_2 discharge into water bodies would be dissolved and precipitated, thus reducing CO_2 flux into the atmosphere.

Figure 9 *Upward discharge of saline water and accumulation of mineral precipitate at an open artesian (flowing) borehole at the south shore of Great Slave Lake, NWT, Canada (picture: K.U. Weyer, 1977; Weyer 2010a)*

Figure 10 *Upward natural discharge of saturated brine and precipitated salt near Salt River, NWT, Canada. (picture: K.U. Weyer, 1977, Weyer 2010a)*

Field examples of upward discharge of saline groundwater and saturated brine: A persistent stumbling block in understanding the application of Hubbert's force potential to the geologic storage of CO_2 is the ill-informed notion that in the subsurface, under hydrodynamic conditions, light fluids always move upwards following the so-called and assumed vertical direction of buoyancy forces, while heavier fluids move vertically downwards. That notion is routinely applied for CO_2 storage in saline aquifers to the degree that it is claimed that dissolution of CO_2 in saltwater would increase its density and thereby make certain that this salt water would flow to the bottom of the geological layer system and would never migrate upwards again. That assumption is completely incorrect.

With respect to the lighter material Weyer (1978, 2010a) has elucidated under which commonly encountered conditions of 'Buoyancy Reversal' lighter fluids move downwards instead of upwards. Here we show by means of pictures the upwards discharge of saline water through an open borehole at the shore of Great Slave Lake (Figure 9) and that of saturated brine at a site close to the Salt River in the NWT, Canada (Figure 10). Weyer *et al.* (1979) indicate the brine to contain about 25% TDS; its chemical content was >300,000 ppm. In spite of the high density of the brine the local gradients of the groundwater flow system were sufficient to force the saturated brine to the surface. This simple optical evidence should suffice to cause the abandonment of widespread misconceptions on the role of buoyancy when injecting CO_2 at on-shore sites.

Conclusions

- Off-shore subsurface fluid flow is governed by 'buoyant' behaviour, on-shore flow is not.
- All on-shore fluid movement is dominated by the force fields of fresh groundwater.
- The hydrogeological methodology for the study of regional gravitational groundwater flow systems needs to be applied to the storage of CO_2.
- Migration routes and discharge points to the surface can be determined for stored CO_2 as can the approximate amounts and velocities of flow.
- So far, application of groundwater flow system theory to CO_2 storage is practically non-existent.
- At the bank of the Green River in Utah, Crystal Geyser provides an example of CO_2 discharge via deep-seated groundwater flow systems into a major river without any obvious ill-effects.
- If location and target layers are properly chosen, migration from CO_2 storage sites by groundwater flow systems will eventually reach major surface water bodies only after thousands or tens of thousands of years in all likelihood without any ill-effects for environment and climate.
- More focus needs to be placed on research into the interaction between groundwater flow systems and CO_2 storage, the geochemical reactions encountered along the flow path of CO_2, as well as integrating the methodology of groundwater dynamics (hydrodynamics) and reservoir engineering.

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