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Differing physical processes in off-shore and on-shore CO_2 storage

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Abstract

The geological 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.

Geological 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 a subsurface fluid mechanics, adopted to CO_2 sequestration, will need to apply Hubbert's Force Potential [1,2] which relates energy to mass and does not need to assume incompressibility or vertical buoyancy forces, as well as Groundwater Flow Systems Theory.

Keywords: CO_2 storage, migration, groundwater flow systems, Hubbert's force potential, hydrodynamics

Introduction

In carbon sequestration, the 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 [3] 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 [1,2] established (Figure 1) that the so-called 'buoyancy forces' are pressure potential forces, which are directed vertically upwards and vertically downwards under hydrostatic (no gravitationally driven flow) conditions but which, under hydrodynamic conditions (gravitationally driven flow), are directed in an oblique fashion. Within low

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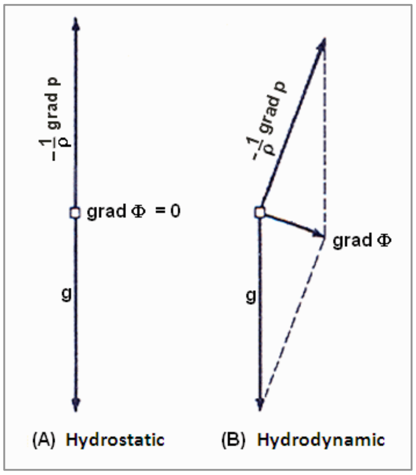

Figure 1

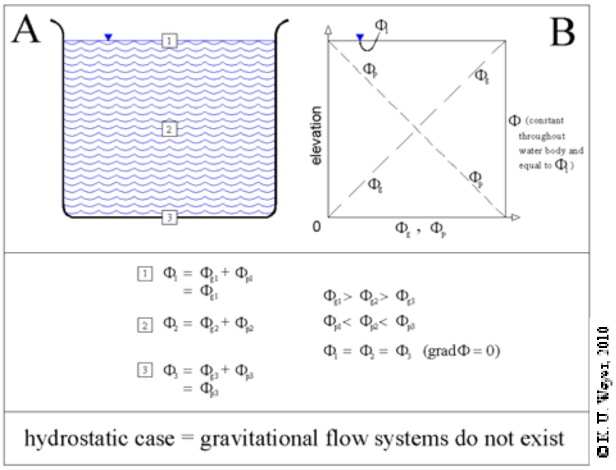

Figure 2

Figure 1 Hydrostatic forces versus hydrodynamic forces (after Hubbert [2]).

Figure 2 Hydrostatic conditions in a pail (from Weyer [3]). The value of the fluid potential Φ is constant throughout the water body (part A) and determined by the surface elevation according to the equation Φ = hg (Weyer [4]) where h is the head and g the earth acceleration. The gravitational potential Φ_g and the pressure potential Φ_p , however, change in synchronous opposition with depth (part B) such that the gravitational potential Φ_g decreases with depth (part B; line Φ_g) at the same rate as the pressure potential Φ_p (part B; line Φ_p) increases with depth.

Therefore the additions of the gravitational and pressure potential return the same hydraulic potential Φ, namely that of the surface, at all positions within the water body in the pail. Within the hydrostatic water body, the gradient of the hydraulic potential is 0 (grad Φ = 0) and no gravity-driven flow occurs.

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:

$$\Phi = \Phi_g + \Phi_p \qquad (1)$$

The gradients of these energies are the vectoral forces propelling subsurface fluid flow whereby $\vec{g}$ is the earth's acceleration, p is the pressure and ρ is the density of the fluid considered:

$$-\text{grad}\,\Phi = \vec{g} - \frac{\text{grad}\,p}{\rho} \qquad (2)$$

The respective physics is explained by Hubbert [1,2,5,6] and Weyer [4]. In this paper we will concentrate of 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:

$$\Phi_1 = \Phi_2 = \Phi_3 \qquad (3)$$

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 (Figure 3A). The gravitational potential Φ_g and the pressure potential Φ_p are, however, conjoined (see Figure 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 in equation (3) 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 geological 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.

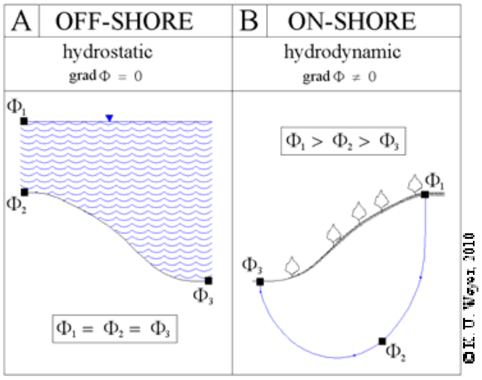

Figure 3

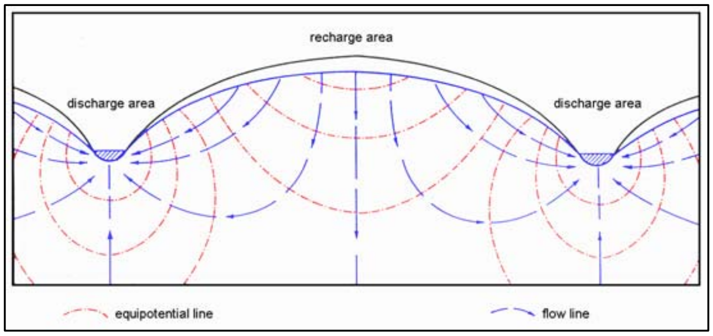

Figure 4

Figure 3 Comparison of hydrostatic and hydrodynamic conditions in subsurface fluid flow (from Weyer [3]. [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 [1], Figure 45)

Figure 3 compares the flow conditions at off-shore sites (Figure 3A) with on-shore sites (Figure 3B). At off-shore sites, the hydrostatic conditions of equation (3) exist, whilst at on-shore sites hydrodynamic conditions prevail. At on-shore sites, the energy conditions along the gravitational flow path are such that

$$\Phi_1 > \Phi_2 > \Phi_3 \tag{4}$$

and groundwater flow systems can reach from the groundwater table to depths of five kilometers or more depending on the topography of the groundwater table and the sequence of geological layers (see model results by Tóth, [7,8] and Freeze & Witherspoon [9]). Freeze and Witherspoon [9] 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 [3, p.15, 16].

Effect of Gravitational Groundwater Flow Systems on On-Shore Storage

Hubbert ([2], p. 1960) established that, on-shore, the force fields of fresh groundwater determine the migration behaviour for salt water, oil, natural 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 [2] 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 on-shore injection sites presently tested for future CO_2 storage. Figure 4 depicts the gravitational groundwater flow pattern determined by Hubbert [1]. 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 [7]. 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: Figures 5 and 6 show an example from Weyer and van Everdingen [10] of 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 and discharging ocean-type salt water back to the surface. For the cross-sectional flow model contrasts permeabilities were assigned according to the geological cross-section of public 1:25,000 geological maps. As such, the flow direction could be determined but not, however, the amount and velocities of flow. (For details of methods used see [10] and [11]).

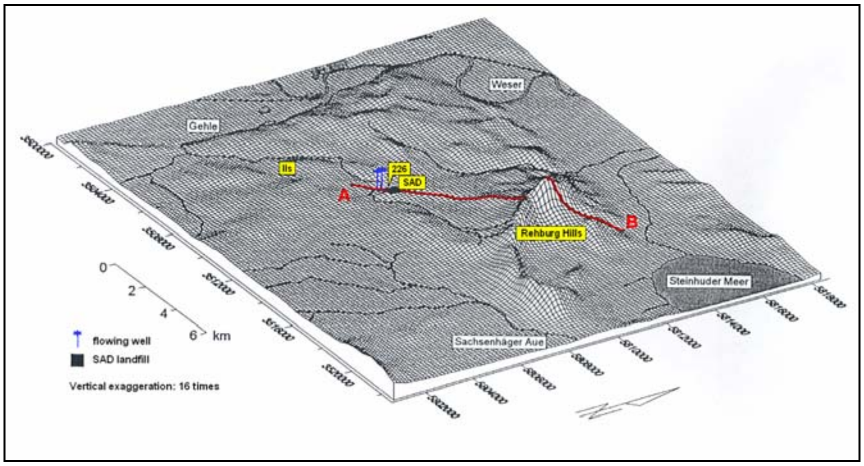

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Figure 5 Digital Elevation Model [DEM] of the area of the landfill Münchehagen [SAD] (after Weyer and van Everdingen [10])

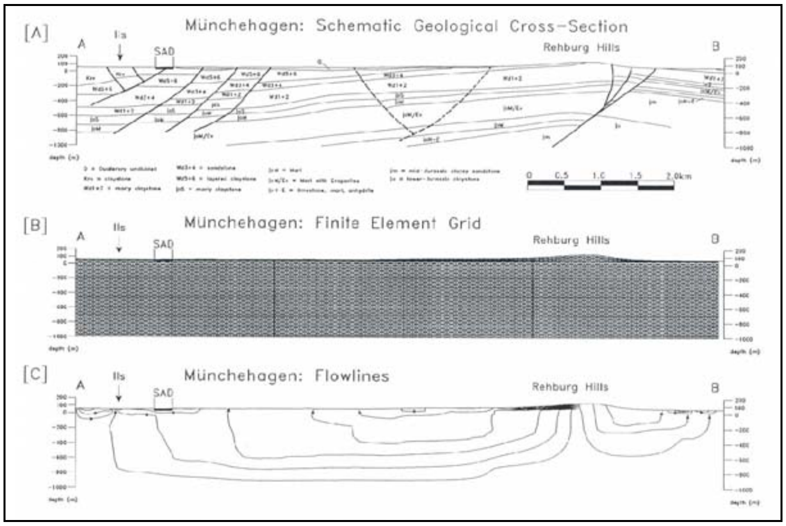

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Figure 6 2D-vertical model of groundwater flow directions in cross-section A-B in the Münchehagen landfill area (after Weyer and van Everdingen [10]).

The results of the flow modelling have been confirmed by field data gathered by independent investigations. Figure 7 indicates the results of hydrogeological investigations reported by Lüdeke [12]. At the site, salt water was discharging upwards into a small river. The shape of the salt water / freshwater boundary had been upwardly deformed by the pumping of fresh water out of a pit in the landfill. Figure 7 also locates, in the map insert, the position of testhole 226 which recorded permeability measurements and the chemistry of the water present at different borehole depths. These data are shown in Figure 8. Saltwater with the salinity of ocean water was encountered at a depth of approximately 50 m at a layer with slightly higher permeability as compared to adjacent layers. The first run of the Münchehagen model also determined the depth to salt water to be about. 50 m (Figures 6 and 9.)

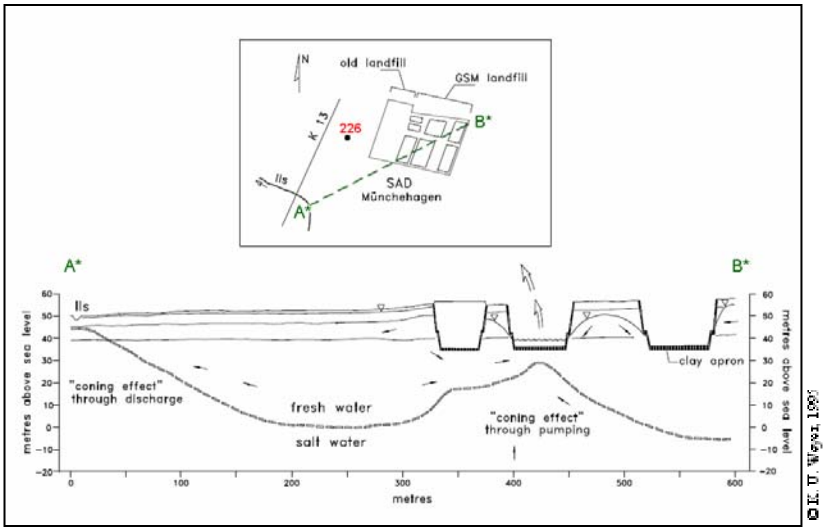
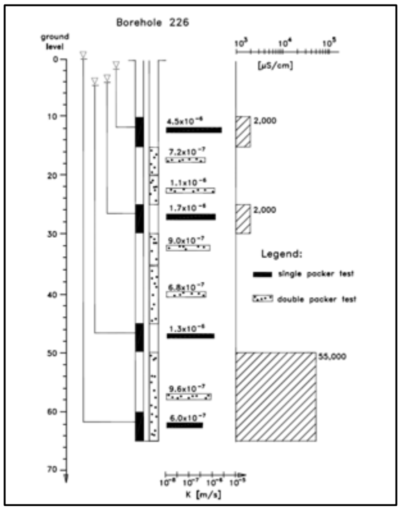


Figure 7 Discharge of saline water at the Ils river with natural discharge and at the Münchehagen landfill site with pumping-induced discharge (after Lüdeke [12], Figures p. 242 and p. 243), from Weyer and van Everdingen [10] .



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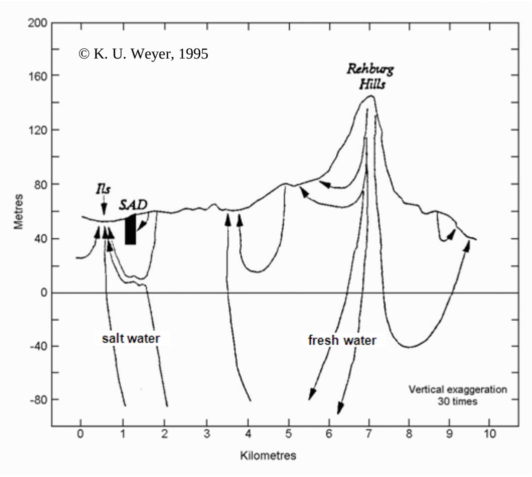

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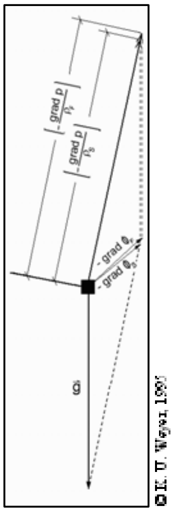

Figure 10

Figure 8 Occurrence of saline water of ocean water type electrical conductivity at a depth of about 50 m below ground in borehole 226 (Gronemeier et al [13], Figure 11)

Figure 9 Cross-section A-B showing flow lines calculated by 2D-vertical mathematical model; vertical exaggeration 30:1; SAD = landfill Münchehagen (after Weyer and van Everdingen [10]).

Figure 10 Similarity in flow directions between fresh water and ocean-type (conductivity 55,000 µS/cm; TDS about 35,000 ppm) salt water (after Weyer and van Everdingen [10]).

Figure 10 explains why recharged fresh water flow systems may discharge water with increased density (in this case a density equivalent to ocean water at 1.03 g/cm^3). The small density difference of only 0.03 g/cm^3 leads to nearly the same flow directions for fresh water and ocean-type saltwater. That is the reason why, to a large degree, these cases can be modelled with single-phase fresh water models (Weyer [3], Weyer and van Everdingen [10]).

Weyburn case: Figures 11 and 12 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.

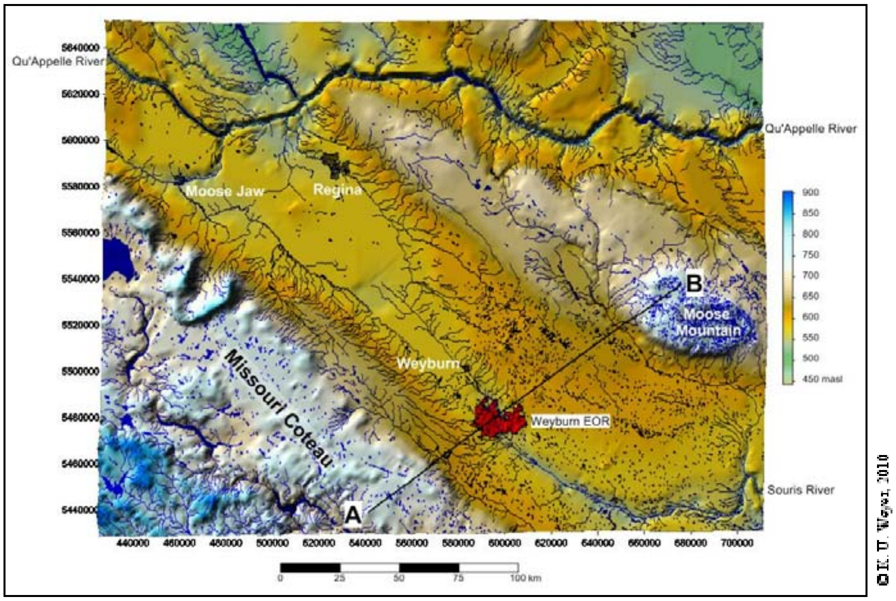

Figure 11 Bird's-eye view of the DEM for the general Weyburn area based on NTDB 1:250,000 digital maps 062E (Weyburn), 062L (Melville), 072H (Willow Bunch Lake) and 072I (Regina). Topographical cross-section A-B is shown in Figure 12. (from Weyer [3])

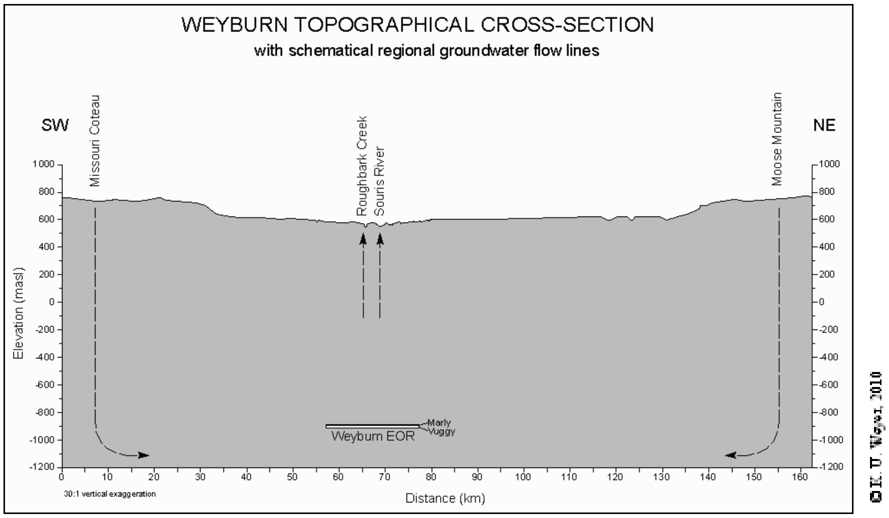

Figure 12 Topographical cross-section A-B from Missouri Coteau to Moose Mountain with elevation differences well in excess of 200 m. The elevations have been taken from the 1:250,000 and, in the Weyburn area, from the 1:50,000 NTDB maps. For location of cross-section, see Figure 11, (from Weyer [3]).

Green River, Utah: Figure 13 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 14. 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 River, the discharge of CO_2 is not only manifested by artesian flow through an open exploration borehole (Figure 13) 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 [3]. CO_2 discharge into water bodies would be dissolved and precipitated, thus reducing CO_2 flux into the atmosphere.

Figure 13

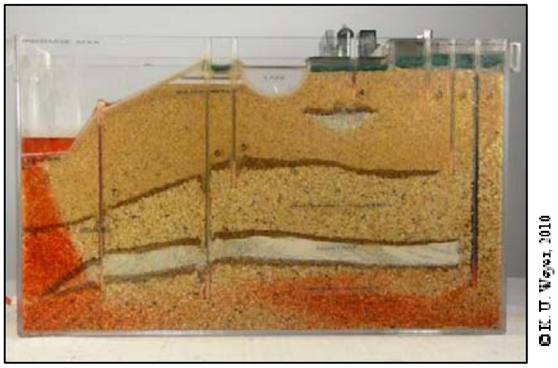

Figure 14

Figure 13 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. (From Weyer [14], picture taken by Weyer, Feb 2010)

Figure 14 Demonstration of deep groundwater flow with dissolved CO_2 entering a surface water body from beneath in a table-sized sand model. (From Weyer [14])

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 geological 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 [3, 4] has elucidated under which commonly encountered conditions (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 15) and that of saturated brine at a site close to the Salt River in the NWT, Canada (Figure 16). Weyer et al. [15] 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.

Figure 15

Figure 16

Figure 15 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; taken from Weyer [16])

Figure 16 Upward natural discharge of saturated brine and precipitated salt near Salt River, NWT, Canada (picture: K.U. Weyer, 1977, taken from Weyer [16]))

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 through groundwater flow systems will eventually reach major surface water bodies only after thousands or tens of thousands of years in all likelihood without ill-effects. 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 methods of groundwater dynamic (hydrodynamics) and reservoir engineering.

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