Trapping CO2 by Means of Subsurface Water Flow

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Introduction

Hubbert, 1953, p.1960 showed that the force potentials (energy / unit mass) of fresh groundwater and the derived force fields determine the flow behaviours of other fluids such as air, 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:

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

This presentation will concentrate 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. That is the reason why groundwater flow occurs everywhere in the subsurface and the flow systems are regional and continuous.

Modelling of Subsurface Fluid Flow

Fig. 1 shows the limited range of reservoir simulators which take caprock as the upper boundary and deal with 'confined' flow only. Groundwater flow modelling, however, takes the groundwater table as the upper boundary and can calculate the force fields and groundwater flow to great depths, including through caprocks and reservoirs. As shown above, these groundwater force fields, under natural conditions, determine the migration behaviour of all other fluids in the subsurface. "*CO_2 injection involves dominantly hydrogeological (single-phase flow) processes in much of the reservoir and surrounding adjacent strata, with additional two-phase flow effects around the CO_2 plume itself*." [Chadwick et al., 2009]

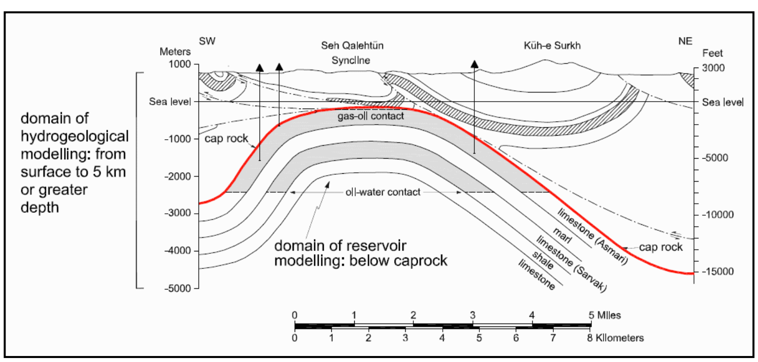

Fig. 1

SW-NE cross-section through the Gachsaran field with oil in the Asmari Formation and the Sarvak Formation in Iran. Figure modified after Dickey (1981, Fig.10-9) and Croft (2002).

"[A] *sand-shale boundary* [is] *an impermeable barrier to oil trapped in the sand, but not an impermeable barrier to the passage of water in either direction*" [Hubbert, 1953, p.1979]. If pressure (i.e. pressure gradient) is applied to the oil [CO_2] in the sand greater than the opposing capillary pressure (gradient) against the oil in the shale, oil [CO_2] will penetrate the shale. Fig. 2 shows downward-directed water flow penetrating the caprock and the hydrocarbon accumulation in a reservoir. While this phenomenon cannot be modelled by the widely-used reservoir simulators, it can be modelled by advanced hydrogeological modelling software.

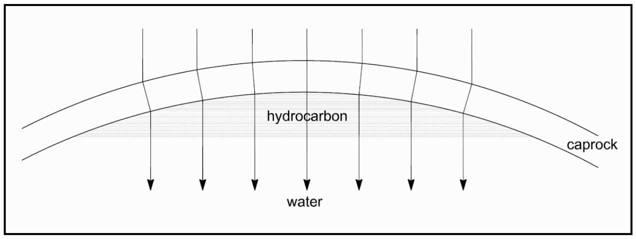

Fig. 2

Schematic of downward-directed water flow penetrating hydrocarbon accumulation and caprock. Due to capillary forces, hydrocarbons normally do not penetrate caprock while water does in either direction (upwards or downwards).

With respect to strong downward flow through caprock and aquitards, Weyer (1978) postulated the occurrence of downward-directed pressure potential forces ('buoyancy' forces) which he termed 'Buoyancy Reversal'.

Buoyancy Reversal

Buoyancy Reversal can occur under conditions of strong downward flow through low-permeable layers. In such a case, the pressure can decrease with depth (Fig. 3) as energy is taken from the compressed fluid element (pressure potential) to maintain the amount of flow, thus causing reductions in pressure and a downward-directed pressure potential force or 'buoyancy' force (Weyer, 2009). Under downward flow conditions, Buoyancy Reversal occurs when grad Φ > 9.81 m/s^2.

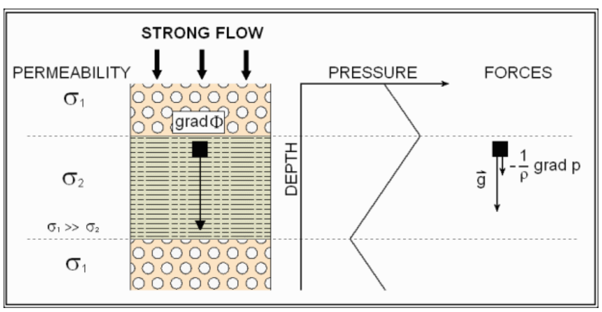

Fig. 3

Distribution of forces at 'Buoyancy Reversal' (modified from Weyer, 2009)

grad Φ	=	resultant hydraulic force
$-\vec{g}$	=	gravitational force
$-1/\rho \cdot$ grad p	=	pressure potential force

Hitchon et al. (1989) described those conditions for the Clearwater-Wilrich Aquitard in the Swan Hills region of Alberta, Canada (Fig. 4, 5). Fig. 6 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.

The conditions giving rise to Buoyancy Reversal are usually created by downward flow from recharge areas through aquitards into high-permeable layers at depth. In the case of Swan Hills, the area with pronounced downward flow seemingly exceeds 10,000 km^2 as evidenced by sites A, B, and C in Fig. 4. In general, areas with deep downward flow are much larger than discharge areas with upward flow from depth.

Due to the downward-directed pressure potential force ($-1/\rho \cdot$ grad p), layers with Buoyancy Reversal act as an additional line of defence 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.

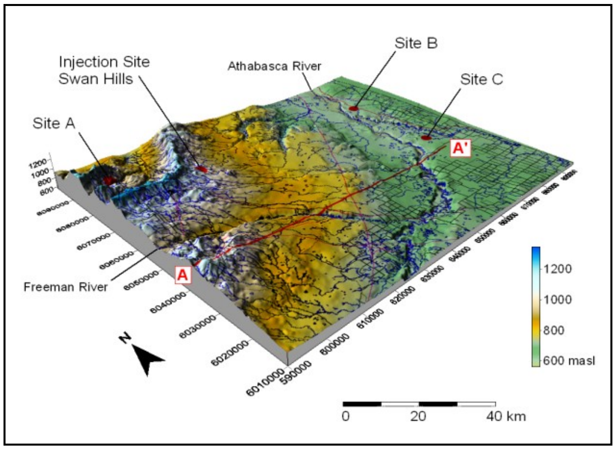

Fig. 4 Digital Elevation Model [DEM] of the Swan Hills area, Alberta, Canada. The geologic cross-section A-A' is marked as a red line (see Fig. 6). At the sites A, B, and C the occurrence of Buoyancy Reversal was measured within the Clearwater-Wilrich aquitard by Hitchon.et al. (1989).

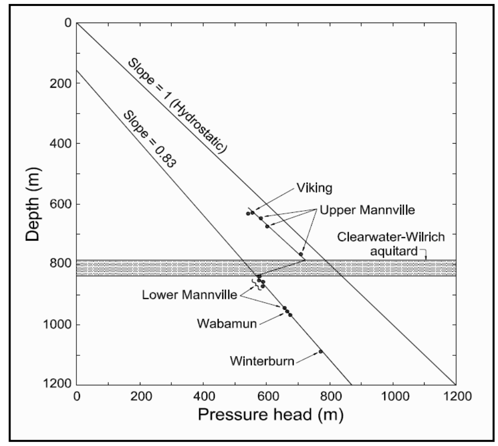

Fig. 5 Buoyancy Reversal at Site A within the Clearwater-Wilrich Aquitard (after Hitchon et al, 1989).

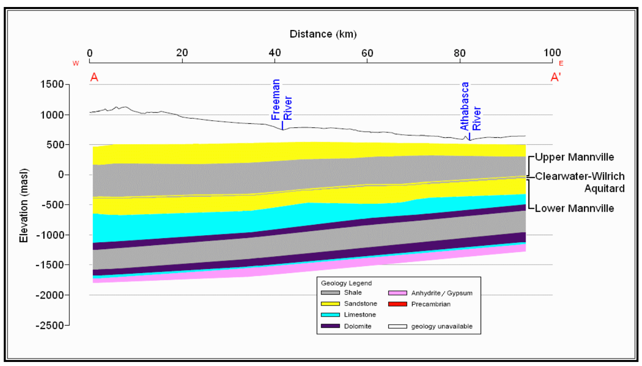

Fig. 6

Geologic cross-section A-A'. See Fig. 4 for location of cross-section.

Effects of Oil Production and CO_2 Injection Upon Fluid Flow

Within an operating reservoir, hydraulic sink conditions are created (Fig. 7) and any Buoyancy Reversal present would be enhanced or possibly newly created because of reduction of fluid potential in the reservoir.

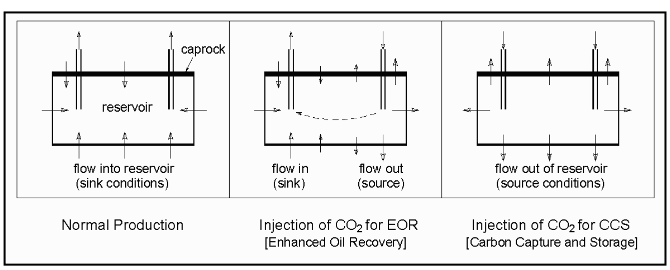

Fig. 7

Changes of sink towards source conditions within a reservoir during petroleum production, EOR and subsequent CCS.

As EOR and carbon storage begin injecting CO_2 at high pressures into the reservoir, the sink conditions shift towards source conditions (Fig. 7). These source conditions would propel water in all directions away from the injection point(s), and thereby potentially eradicate any Buoyancy Reversal present.

There exists, however, a way to maintain Buoyancy Reversal parallel to the injection of CO_2 if the situation warrants it. It would mean to pump water from greater depths within the CO_2

injection layer or beneath it, and subsequently re-inject it above the caprock (Fig. 8), if the water chemistry allows this. Water could also be taken from layers with more favourable chemistry. It is recommended that appropriate field studies be undertaken and that head and pressure be routinely measured above caprocks at planned and operating carbon storage sites.

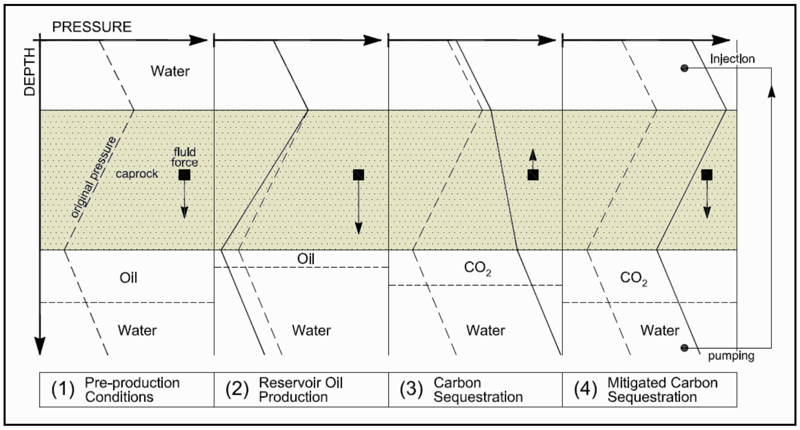

Fig. 8

Schematic pressure-depth relationship at (1) a natural occurrence of Buoyancy Reversal, and subsequent pressure pattern during (2) oil production, (3) carbon sequestration, and (4) mitigation of Buoyancy Reversal through pumping water from beneath the CO_2 layer (or other sources) and injecting it above the caprock.

During injection itself, the behaviour of CO_2 at the injection site is mainly affected by the high injection pressure and gradients at that location although the gravitational forces exist there as well. The further CO_2 migrates from the wells, the more the groundwater force fields take control, albeit with increased pressure potential gradients due to the injection pressure. In general the additional pressure should decrease with the cube of the distance from the injection site, i.e. by a factor of 10^{-9} at about one kilometer distance from the injection site. Hence, although the natural force fields are modified by the introduction of a new source area, much of the flow will, in the end, still be directed towards the major regional groundwater discharge areas established under natural conditions in dependence of the topography of the groundwater table.

Conclusions

- For the modelling of CO_2 migration at storage sites, the use of reservoir simulators should be discontinued and replaced with advanced hydrogeologic modelling techniques. To achieve reliable results and leakage forecasts Hubbert's methodology needs to be merged with parts of the methodology of reservoir engineering.
- Groundwater flow penetrates caprock and aquitards.
- The occurrence of Buoyancy Reversal is widespread in aquitards under elevated areas and may be used for further protection in CO_2 storage, in addition to capillary forces.
- Loss of Buoyancy Reversal could be countermanded by pumping water from below the CO_2 storage (or other sources) and injecting it above the caprock.

References

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