Supplementary Material: Quantifying the Volume of Water Influx into a Gas Reservoir

Due to the Hewett Upper Bunter Sandstone reservoir and the North Morecambe Sherwood Sandstone reservoir datasets showing the presence of a water drive when plotted on a Cole plot, it is likely that the OGIP estimated from the P/z plot is an overestimate, as it assumes the reservoir experiences depletion drive. To check this estimate, Equation 1 (after Dake 1978) can be used to estimate a value for the cumulative volume of water influx into a reservoir, W_e:

$$W_e = \frac{G_p - OGIP(1 - E/E_i)}{E} \tag{1}$$

where, G_p is the cumulative volume of produced hydrocarbons, E is the gas expansion factor and the subscript, *i*, denotes initial reservoir conditions.

Within a depletion drive gas reservoir the value of W_e will be zero, or close to it, as there is little or no water encroachment throughout production. However, if a water drive reservoir has been misidentified as a depletion drive reservoir the OGIP may have been overestimated, which would result in an incorrect (negative) value for W_e. Table 2 (a) shows the estimated values of W_e estimated using Equation 1 for the Hewett Upper Bunter Sandstone reservoir and the North Morecambe Sherwood Sandstone reservoir. In both reservoirs, the estimated value of W_e is negative, and therefore further evidence to suggest that the OGIP values estimated originally from the P/z plots are incorrect. If both reservoirs experience a water drive as indicated by their respective Cole Plots, their estimated W_e values should be positive, i.e. they should experience aquifer influx as gas is produced from them.

Aquifer models can be used to estimate W_e, from which a range of OGIP can be estimated. This revised OGIP estimates can then be input to CO_2 storage capacity equations to give a more accurate estimate of CO_2 storage capacity. In this study the unsteady state water influx theory of Van Everdingen and Hurst (1949) was used to estimate the cumulative volume of water influx throughout the productive lifetimes of the the Hewett Upper Bunter Sandstone and North Morecambe Sherwood Sandstone reservoirs.

Aquifers can be classified as radial or linear. In both case studies, the aquifer type is unknown, therefore both radial and linear models were evaluated. Equation 2 can be used to estimate W_e for both a radial aquifer and a linear aquifer:

$$W_e = U\Delta P W_D(t_D) \tag{2}$$

where, U is the aquifer constant, ΔP is the pressure change over the time interval being assessed and $W_D(t_D)$ is the dimensionless cumulative water influx function.

For a radial aquifer, U is defined by Equation 3:

$$U = 2\pi f \varphi h\left(c_{res} + c_{fluid}\right) r_o^2 \tag{3}$$

where, f is a constant used for aquifers which subtend angles of less than 360° and is defined by Equation 4, φ is porosity, h is aquifer height, c_{res} is the matrix compressibility, c_{fluid} is the fluid (water) compressibility, and r_o^2 is the square of the reservoir radius.

The constant, f, can be estimated using Equation 4:

$$f = \frac{(encroachment\ angle)^\circ}{360^\circ} \tag{4}$$

The encroachment angle can be estimated from the reservoir geometry (see Fig. 9 (a)). The Hewett Upper Bunter Sandstone reservoir is fault bounded to the east by the North Hewett Fault and the South Hewett Fault also runs parallel to the western flank of the anticline, although it is thought not to close the reservoir. This implies flow can occur in a N-S orientation (see Fig. 9 (b)). The North Morecambe Sherwood Sandstone reservoir is fault bounded to the east, south and west, therefore the angle of water encroachment into the reservoir is estimated to be 90° from the north (see Fig. 9 (c)).

The dimensionless cumulative water influx function, $W_D(t_D)$, is determined from graphs, after Van Everdingen and Hurst (1949), in Dake (1978), by reading off the value for W_D which corresponds to the point where dimensionless time, t_D, intersects the relevant curve for the dimensionless radius, r_{eD}. Dimensionless time, t_D, and dimensionless radius, r_{eD}, are determined using Equations 5 and 6:

$$t_D = \frac{kt}{\varphi\mu\left(c_{res} + c_{fluid}\right)r_o^2} \tag{5}$$

$$r_{eD} = \frac{r_e}{r_o} \tag{6}$$

where, k is permeability, t is time, μ is viscosity and r_e is the external boundary radius.

It is possible to check the W_D value estimated from the graphs using Equation 5. In cases of bounded aquifers, irrespective of the geometry, there is a value of t_D for which the dimensionless water influx reaches a constant maximum value. The value is dependent upon the geometry as defined in Equation 7:

$$Radial\ W_D = \frac{1}{2}({r_{eD}}^2 - 1) \tag{7}$$

For a linear aquifer, Equation 2 can be used to calculate W_e. However, Equation 3, used to estimate the aquifer constant, U, is modified to Equation 8:

$$U = wLh\varphi(c_{res} + c_{fluid}) \tag{8}$$

where, w is the aquifer width and L is the aquifer length.

Equation 5, used to estimate dimensionless time, t_D, is also modified to Equation 9:

$$t_D = \frac{kt}{\varphi\mu\left(c_{res} + c_{fluid}\right)L^2} \tag{9}$$

Again, $W_D t_D$ is determined from graphs, after Van Everdingen and Hurst (1949), in Dake (1978). However, for linear aquifers, values of W_D are determined by reading off where t_D intersects the line, "finite linear aquifer". It is again possible to check the estimated W_D value: for a linear aquifer the maximum value for W_D is equal to 1. Linear aquifer geometry is shown in Fig. 10, after Dake (1978).

Using the mean estimates of W_e obtained using the finite radial and linear aquifer models, it is possible to obtain values of OGIP for both case study reservoirs through rearranging Equation 1:

$$OGIP = \frac{G_p - W_e E}{1 - E/E_i} \tag{10}$$