Simplified CO_2 volume calculation from time-lag

$$Vol_{CO_2} = \Phi * dx * dy * (1-S_w) * \frac{V_{S_w=1} * V_{(1-S_w)}}{2* (V_{S_w=1} - V_{(1-S_w)})} * (TWT_{99} - TWT_{94})$$

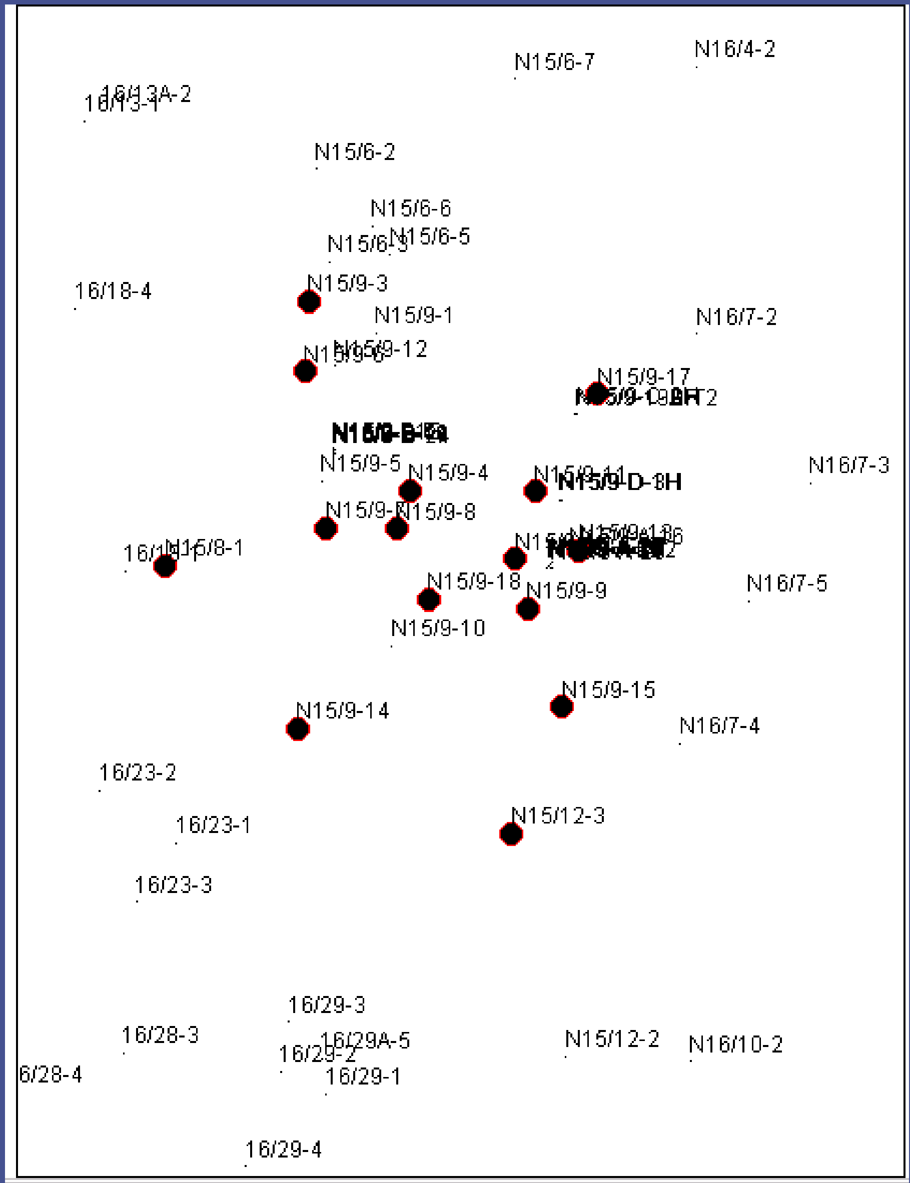
Gassman factor

With:

Vol_{CO_2}	is the volume of CO_2 under reservoir conditions (Rm^3)
$V_{S_w=1}$	is velocity in water saturated sandstone (‘94) (m/ms)
$V_{(1-S_w)}$	is velocity in CO_2 saturated sandstone (‘99) (m/ms)
S_w	is water-saturation and $(1-S_w)$ is CO_2-saturation
Φ	is porosity
dx, dy	are the inline and crossline spacing (product is the bin-size) (m)
TWT_{99}	is an interpreted two-way traveltime picked below the CO_2 after injection (‘99) (ms)
TWT_{94}	is the same interpreted two-way traveltime before injection (‘94) (ms)

Nederlands Instituut voor Toegepaste Geowetenschappen TNO
Netherlands Institute of Applied Geoscience TNO
- National Geological Survey

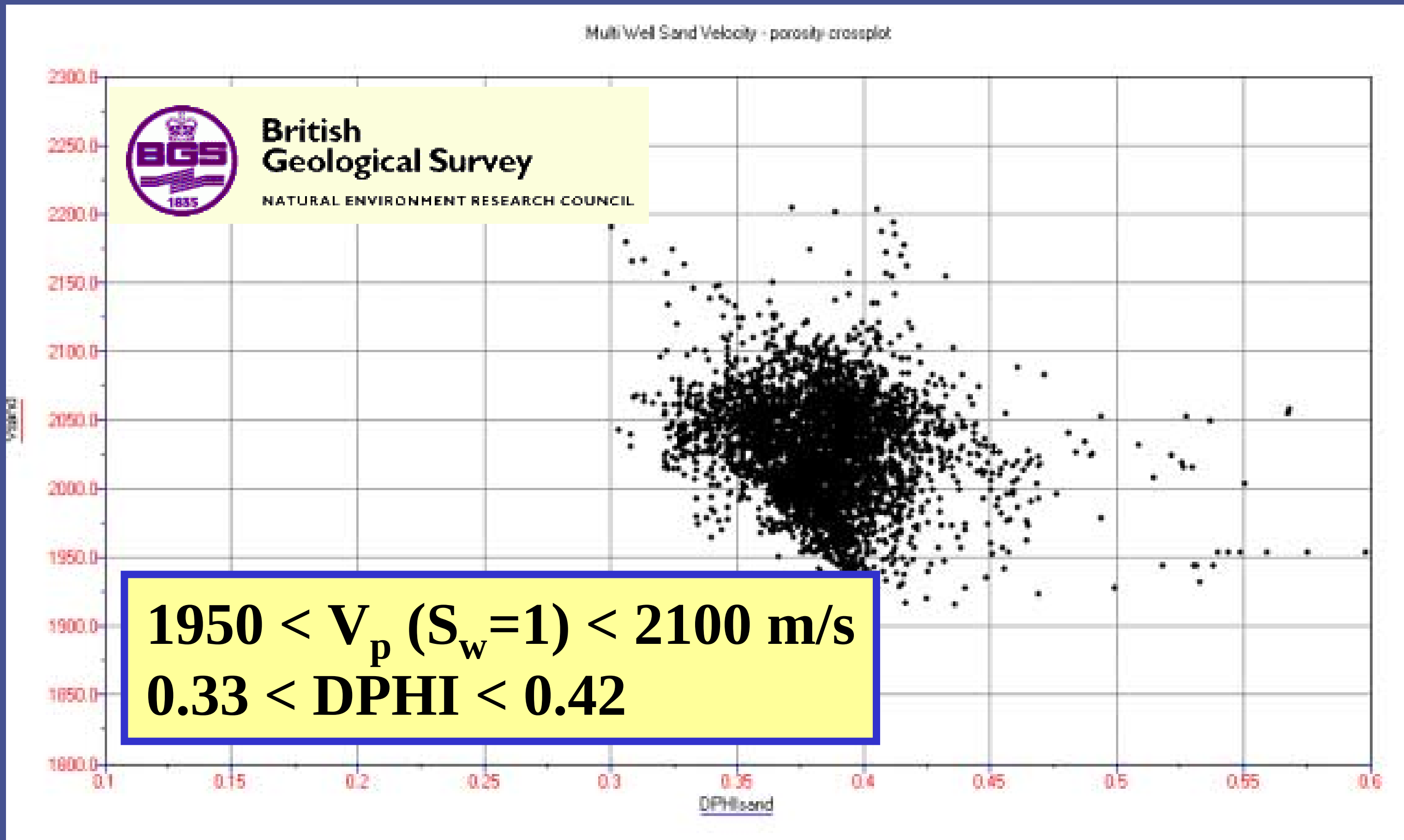
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL



Wells used in cross plots:

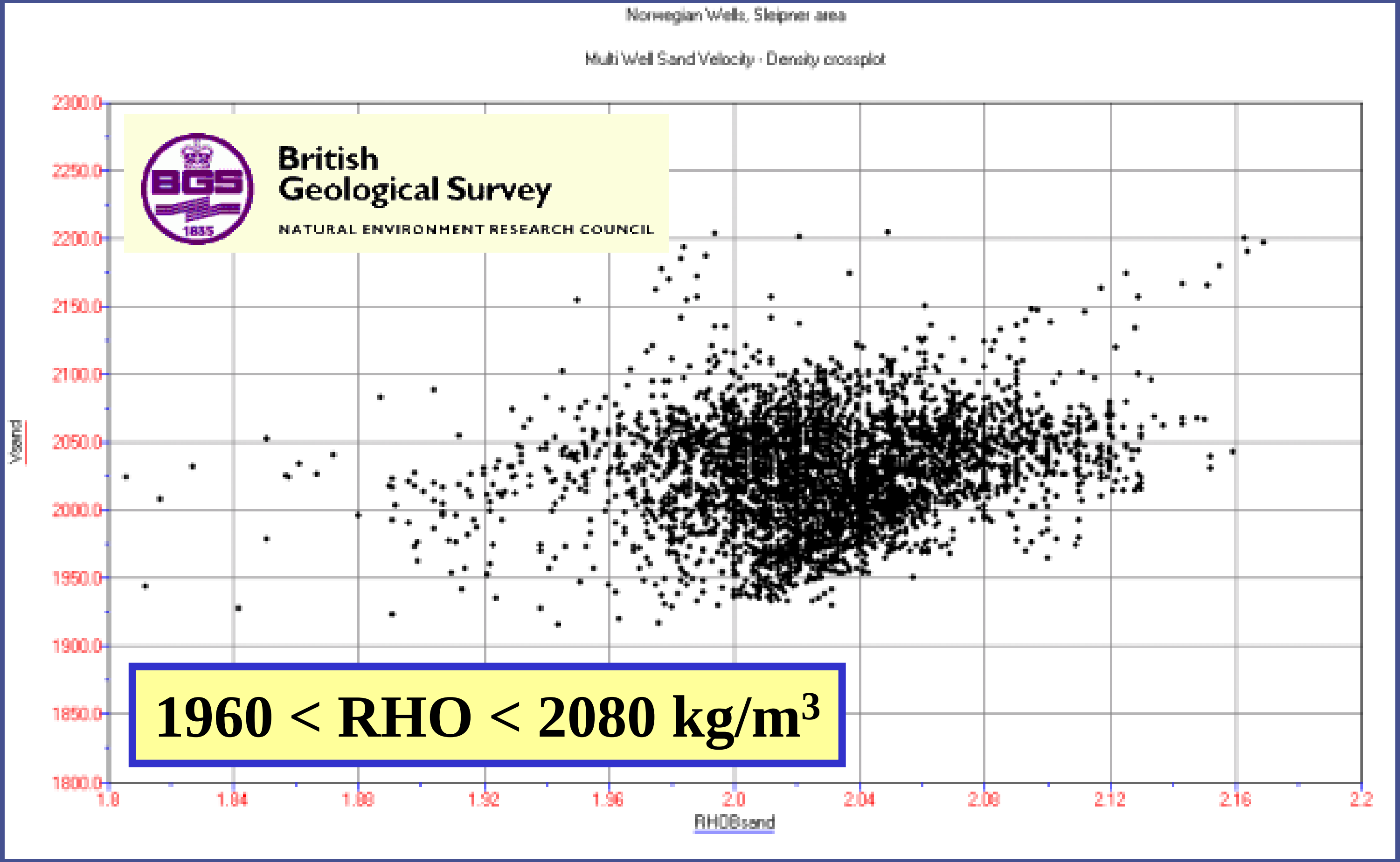
15/12-3
15/8-1
15/9-11
15/9-14
15/9-15
15/9-16
15/9-17
15/9-18
15/9-3
15/9-4
15/9-6
15/9-7
15/9-8
15/9-9

V_p in water saturated sandstone vs. porosity



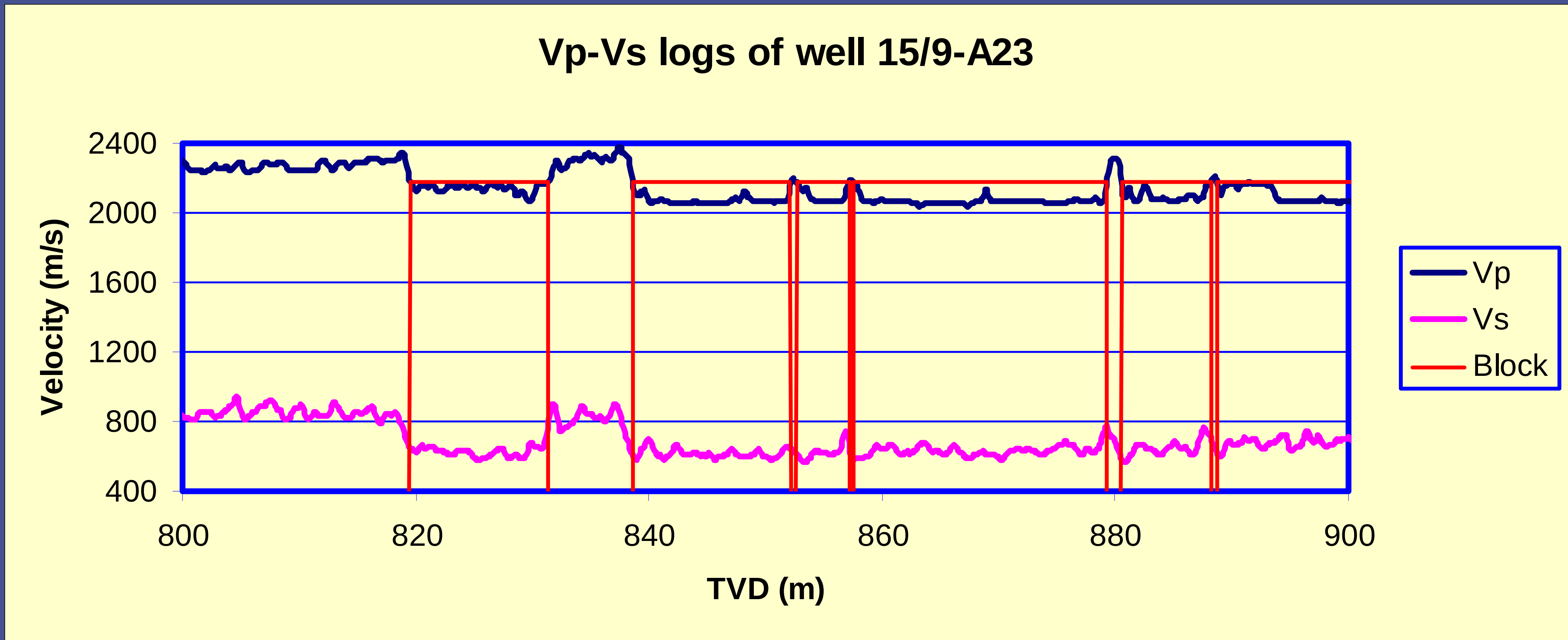
- Gr cut off <37 API used
- Caliper cut off <17.7" used. (8 wells with caliper and density. Wells with no caliper and those with holes bigger than this have not been evaluated)
- Salinity of 40000ppm assumed, giving a fluid density of 1.0325 g/cc
- Matrix density of 2.65 g/cc used (quartz)

V_p in water saturated sandstone vs. density



- Gr cut off <37 API used
- Caliper cut off <17.7" used. (11 wells with caliper and density. Wells with no caliper and those with holes bigger than this have not been evaluated)
- Salinity of 40000ppm assumed, giving a fluid density of 1.0325 g/cc
- Matrix density of 2.65 g/cc used (quartz)

V_p-V_s velocities in water saturated sandstone before CO_2 injection in well 15/9-A23



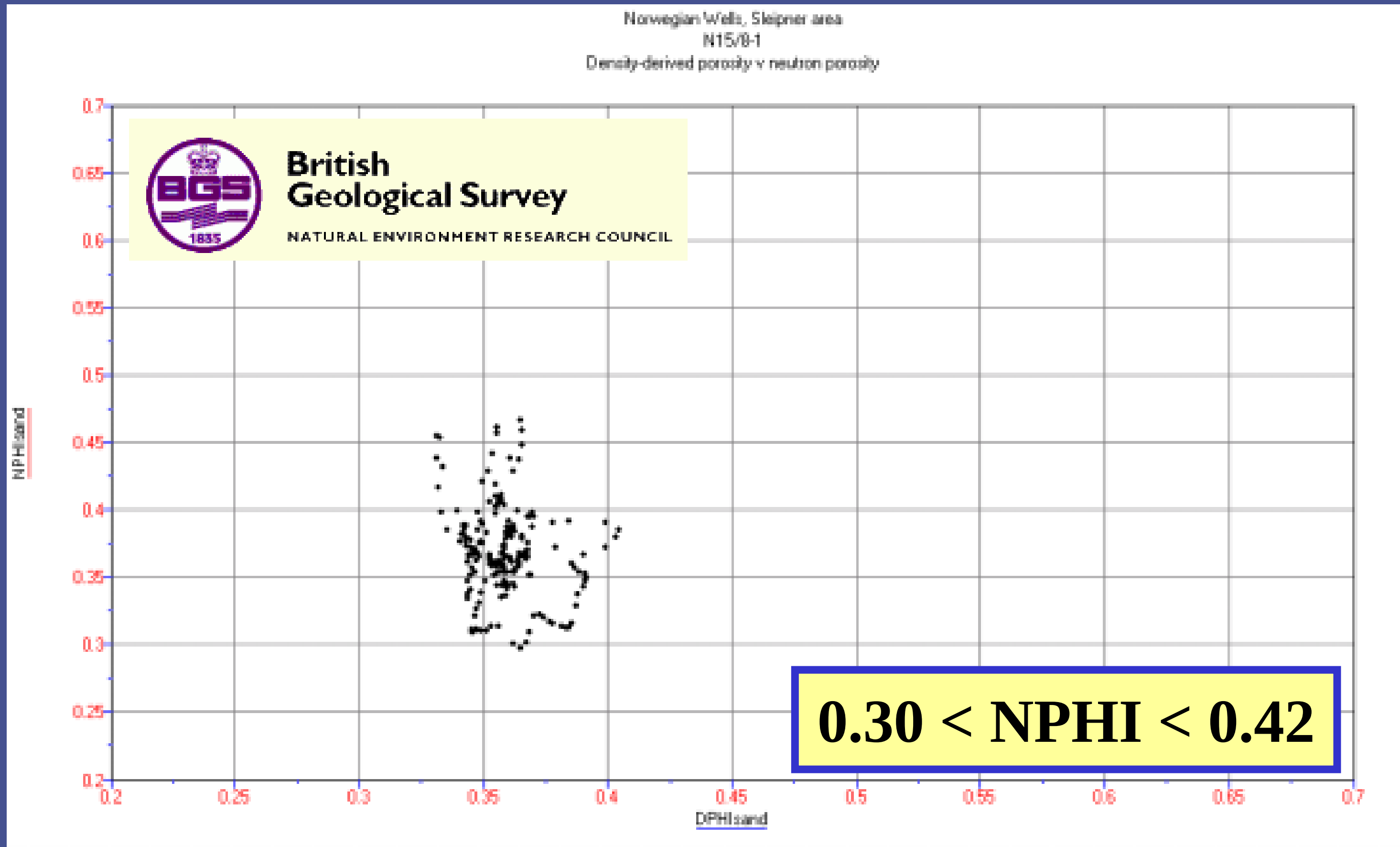
The red blocks indicate the Utsira sands with:

$V_{p,mean}$ = 2090 m/s (higher as mean velocity from 14 wells) and

$V_{s,mean}$ = 643 m/s

$600 < V_s (S_w=1) < 680$ m/s

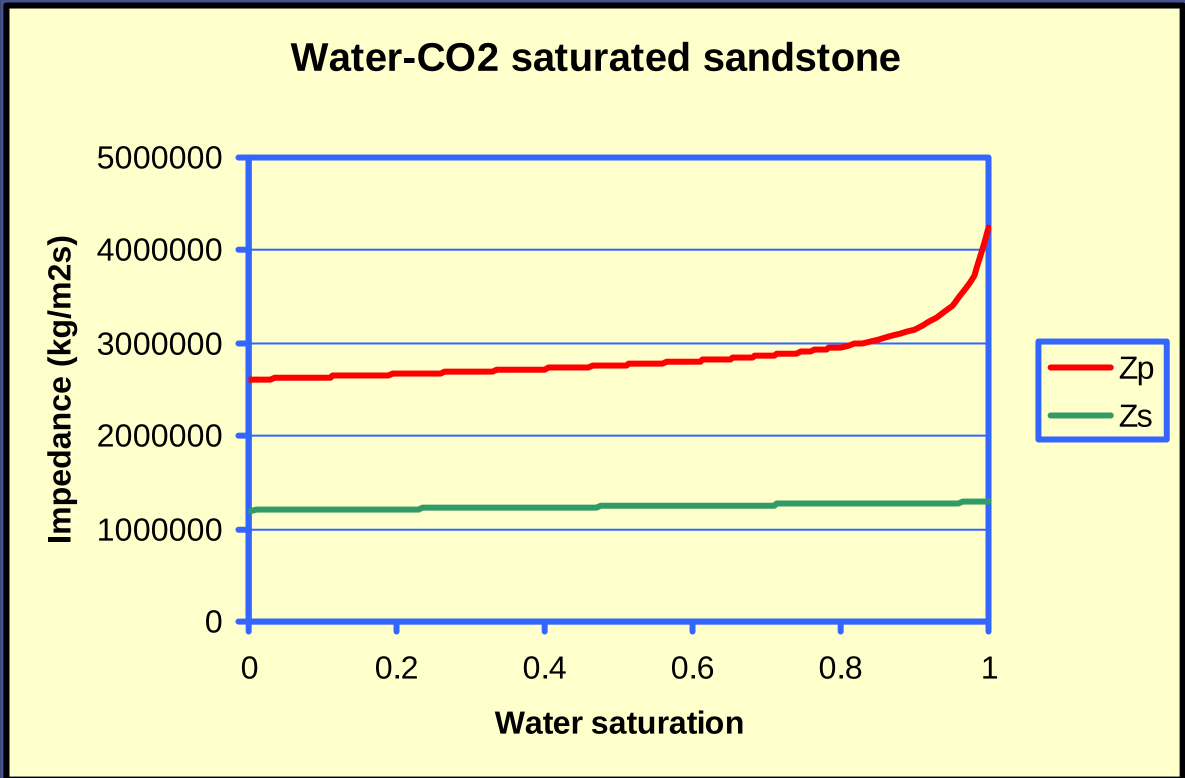
Density derived porosity vs. neutron porosity



- •Gr cut off <37 API used
- •Caliper cut off <17.7" used. Only 1 well has neutron log for Utsira Sand
- •Salinity of 40000ppm assumed, giving a fluid density of 1.0325 g/cc
- •Matrix density of 2.65 g/cc used (quartz)

Gassman modeling with water-CO_2 saturated sandstone (seismic impedances)

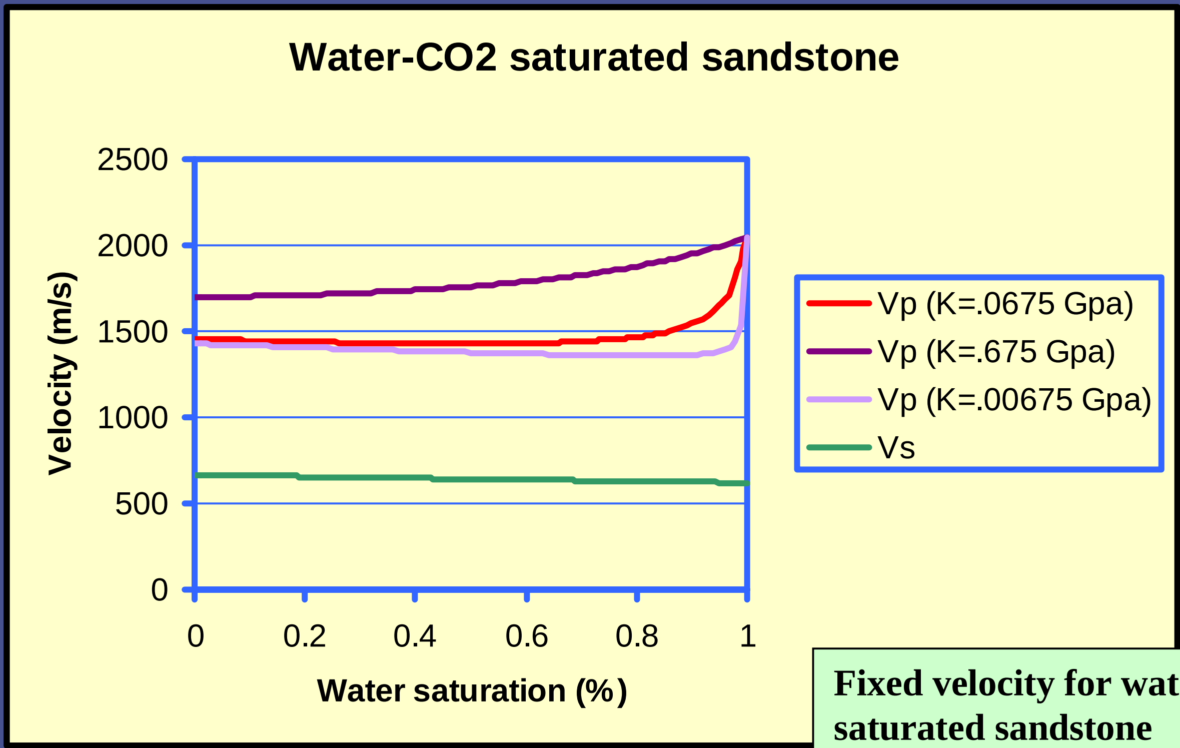
$1300 < V_p\ (S_{co_2}=1) < 1600$ m/s
$K_{co_2} =< 0.0675$ GPa



Parameters:

$V_p\ (S_w=1) = 2050$ m/s
$V_s\ (S_w=1) = 620$ m/s
$\rho\ (S_w=1) = 2073\ kg/m^3$
$\Phi = 37$ %
$\rho_{skeleton} = 2650\ kg/m^3$
$K_{skeleton} = 36.9$ GPa
$\rho_{water} = 1090\ kg/m^3$
$K_{water} = 2.381$ GPa
$\rho_{CO_2} = 340\ kg/m^3$
$K_{CO_2} = 0.0675$ GPa

Gassman modeling with water-CO_2 saturated sandstone using different bulk moduli for CO_2



Fixed velocity for water saturated sandstone of 2050 m/s

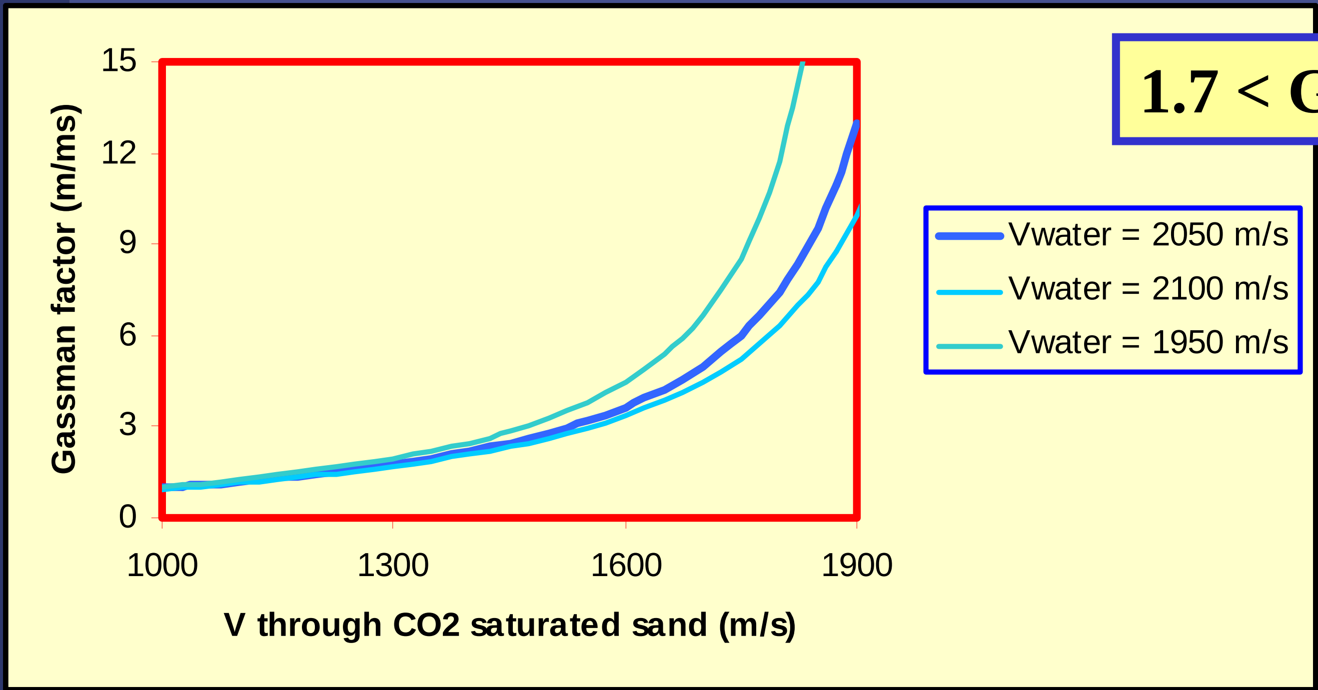
Note:

The bulk modulus K of the CO_2 has a major influence on the shape of the V_p saturation curve.

The most likely K is < 0.0675 Gpa.

The most likely CO_2 saturated velocity range is approximately from 1300 m/s to 1600 m/s for CO_2 saturations up to 95 %.

Gassman factor as a function of the velocity through CO_2 saturated sandstone



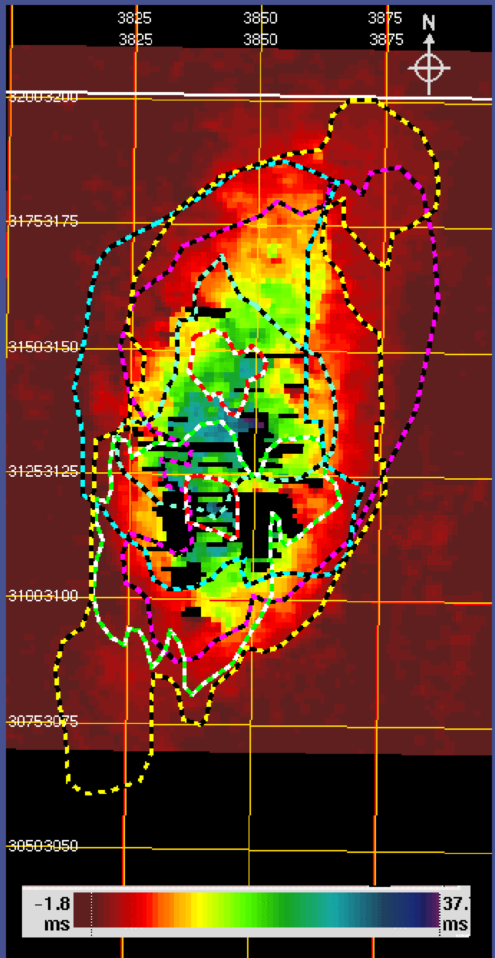
1.7 < Gassman factor < 3.6

Note:

Assuming a velocity of 1600 m/s instead of 1300 m/s through the CO_2 saturated sandstone almost doubles the CO_2 volume estimated from the time-lag data.

The Gassman factor ranges probably from 1.7 to 3.6 for the Utsira.

Time lag due to the lower velocity through CO_2 determined from the seismic post-stack data



$(TWT_{99} - TWT_{94})$:

- Determined by cross-correlating 94-99 surveys
- Range approximately from 0 to 40 ms
- Large uncertainty below the CO_2 bubble
- Undetermined areas have been interpolated

$0 < TWT_{99} - TWT_{94} < 40$ ms

CO_2 volume estimation

Different scenario's for the calculation of the CO_2 volume at reservoir conditions with the most likely case highlighted

Φ (%)	Gassman factor (m/ms)	Volume of CO_2 (10^6 Rm3)
35	2.5	5.99
35	1.78	4.26
35	3.64	8.74
37	2.5	6.34
37	1.78	4.50
37	3.64	9.24

Order of the most likely value (see parameters of Gassman curve)

Injected in October 1999:

•1.29 10^9 Sm^3 (source: Statoil) or

•7.03 10^6 Rm^3 (source: SIMED reservoir simulator)

Conclusions 1

•The Gassman factor has a major influence on the volume estimation (range 1.7 - 3.6). The choice of the velocities in the water saturated medium (1950 m/s < V_p < 2100 m/s and 600 m/s < V_s < 680 m/s) is not of major importance.

•The bulk modulus of the CO_2 is the most important factor determining the Gassman curve. Density plays a minor role. It is expected at the average reservoir conditions (pressure of 80 bar and temperature of 37 degrees Celsius), that the bulk modulus is less or equal to 0.0675 Gpa, leading to a typical gas behavior.

Conclusions 2

- **Because of this gas-behavior, it will be difficult to estimate saturations from impedances:**

- **From 0 % up to 80 % water saturation about 12 % change in impedance is expected.**

- **From 80 % up to 100 % water saturation about 30 % change in impedance is expected.**

- **The reservoir simulator SIMED results in an average density of the CO_2 of ρ = 340 kg/m^3.**

Conclusions 3

•Porosity does not play a major role within the uncertainty range of 30 % to 42 % (most likely case of 35 % to 37 %).

•The time lag estimated from the post stack seismic data is the most uncertain direct data source. Better results on this can only be obtained through pre-stack data analysis.

•The volume estimation of the reservoir simulator SIMED of 7.03 10^6 Rm^3 is in the same order of magnitude and within the uncertainty range of the estimation from the seismic data with the most likely case of 6.34 10^6 Rm^3.