Pressure performance of a large-scale saline aquifer during industrial-scale CO_2 injection: the Utsira Sand

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Pressure response

Key measure of aquifer performance (injectivity and capacity)

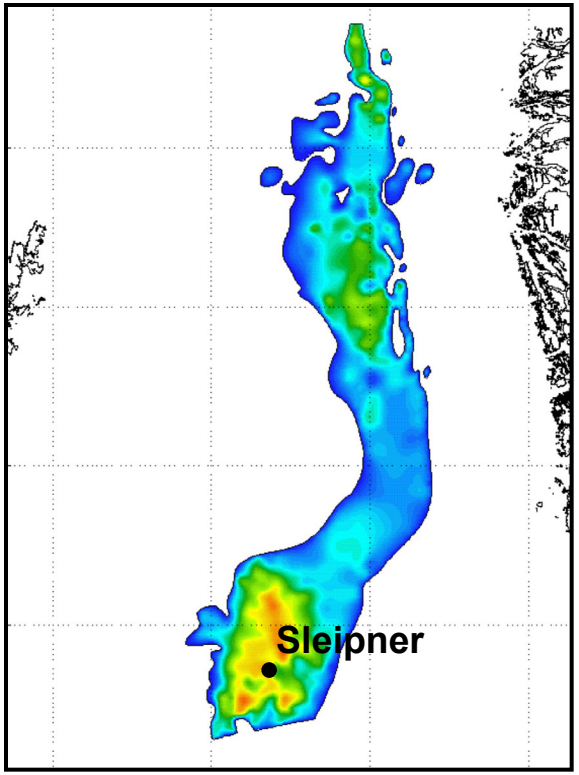
Controversial (e.g. Ehlig-Economides & Economides)

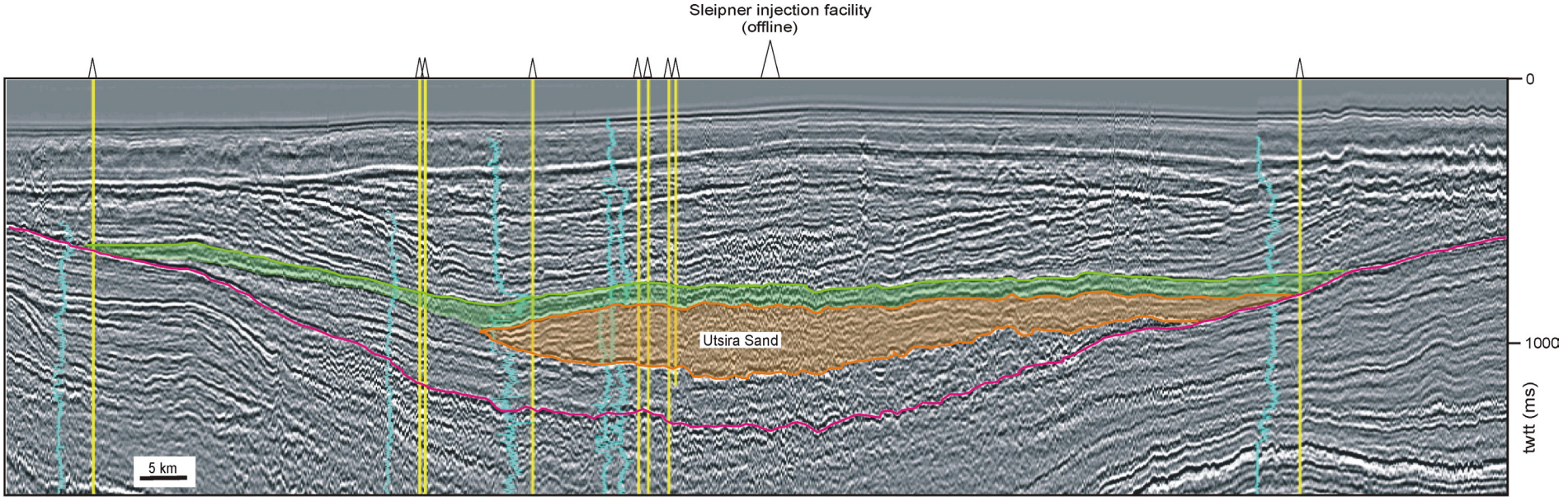
Are aquifers closed or open at their boundaries?

Do internal flow barriers create small ‘closed-systems’ within larger reservoirs?

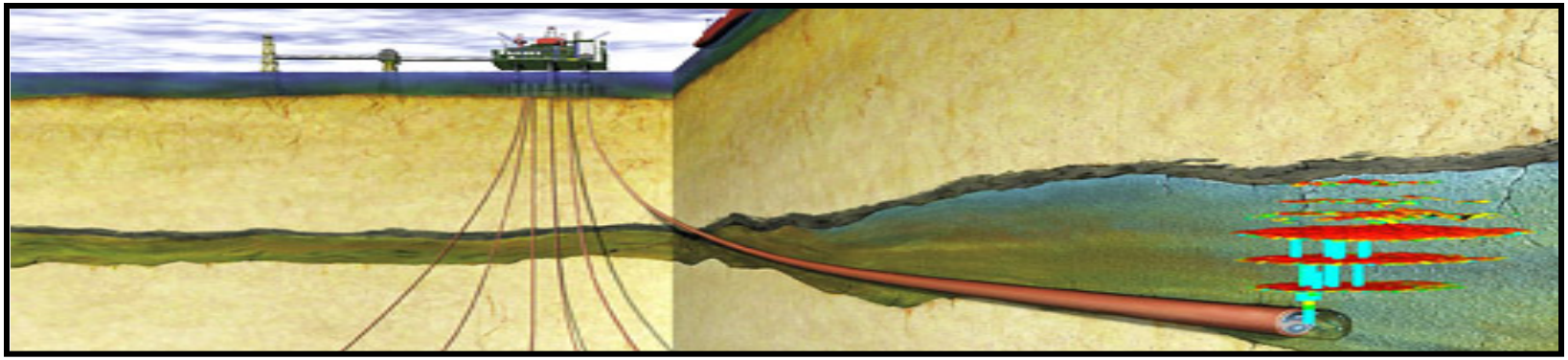
Utsira Sand

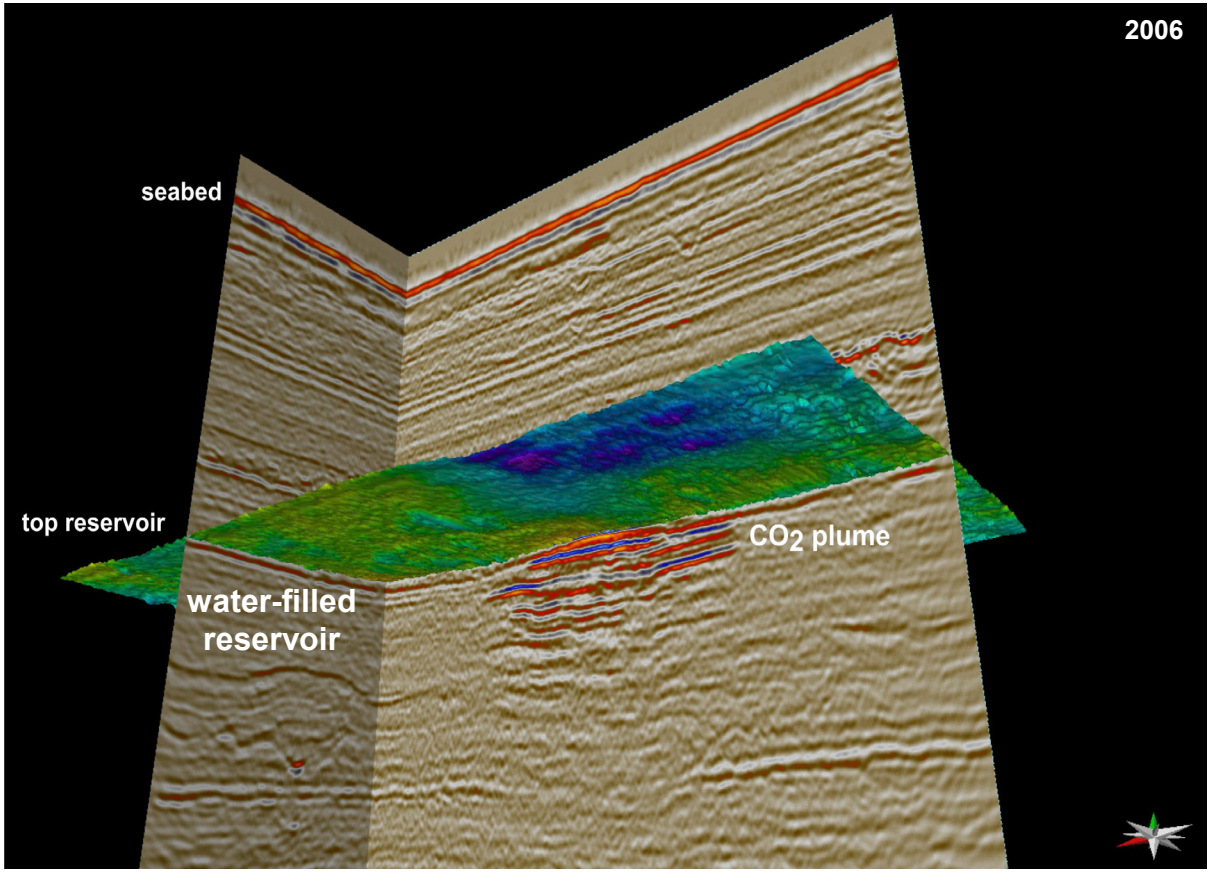
North Sea Basin late post-rift succession
Giant aquifer
Very high permeability
Very high porosity
Negligible faulting





Sleipner CO_2 injection operation





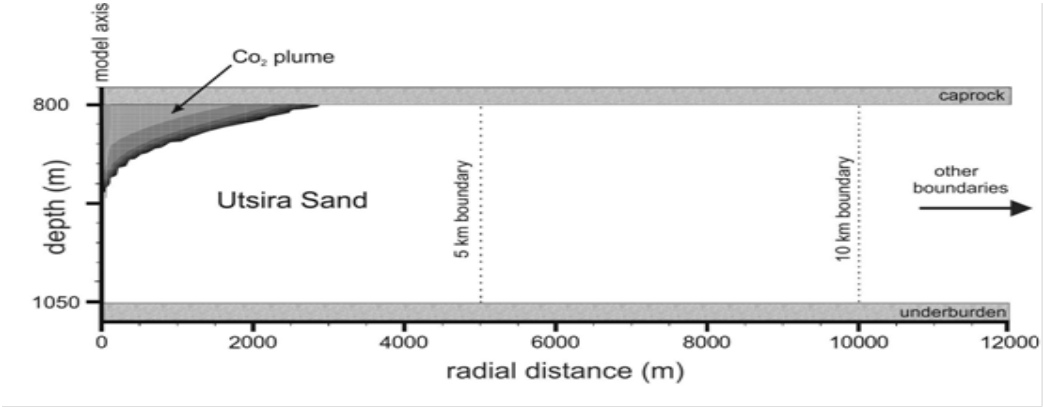
Injection started 1996
~13 Mt CO_2 now injected

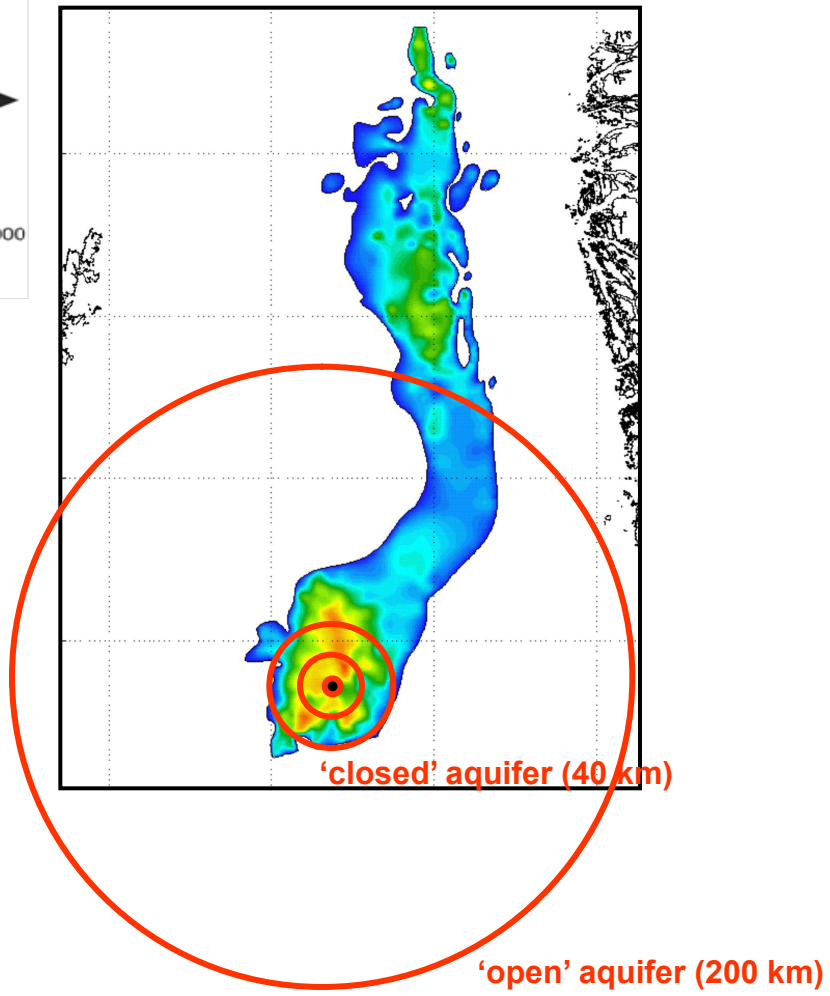
Wellhead pressure monitoring

Time-lapse 3D seismic monitoring over plume and adjacent aquifer

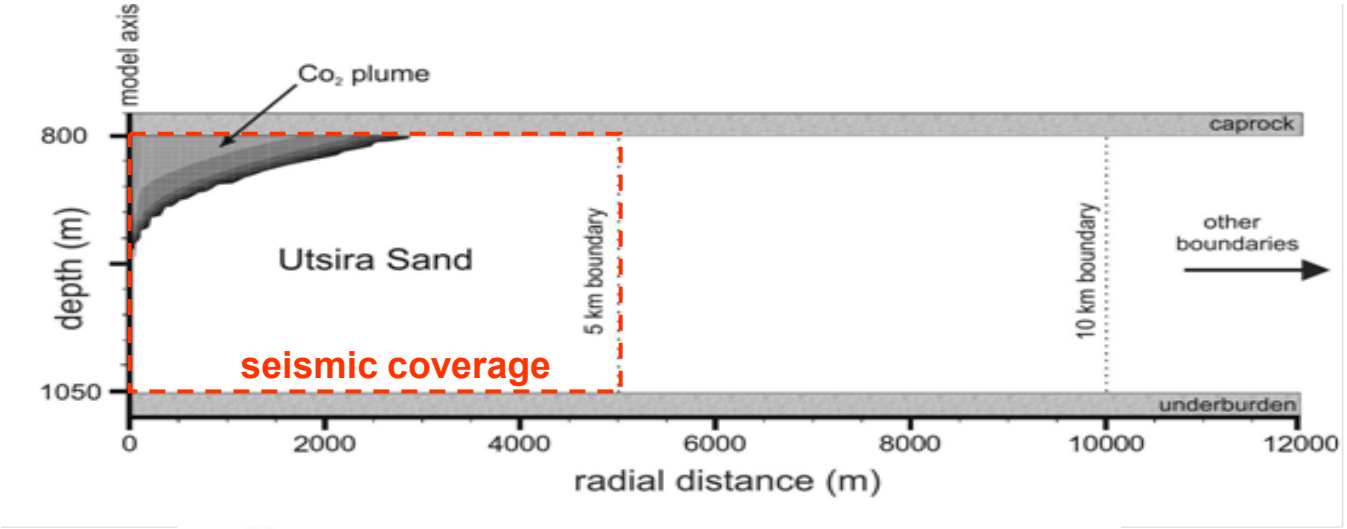
1994 (baseline)
1999
2001
2002
2004
2006
2008

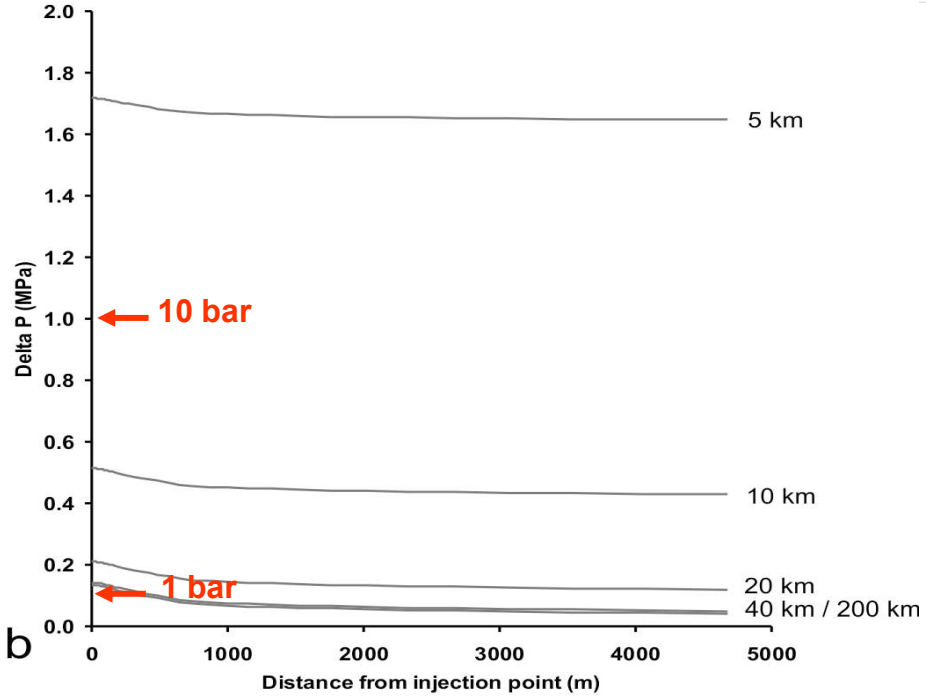
Pressure prediction by TOUGH2 axisymmetric flow model





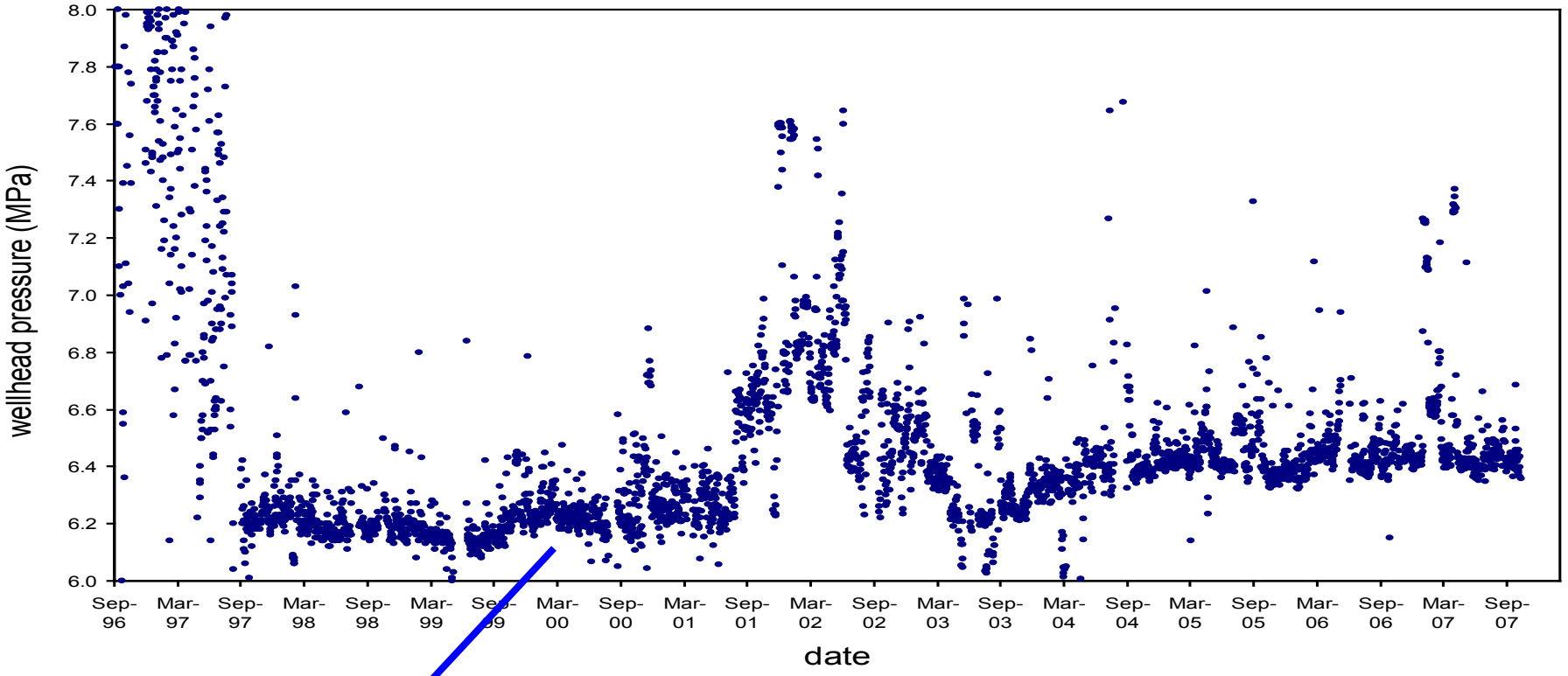
TOUGH2 Pressure simulation for 2006





ΔP > 1 bar suggests flow (pressure) compartmentalisation

Sleipner wellhead pressures



$$P_{IP} = P_{WH} + g\int_0^Z \rho(z)\,dz$$

(plus dynamic terms)

Where:

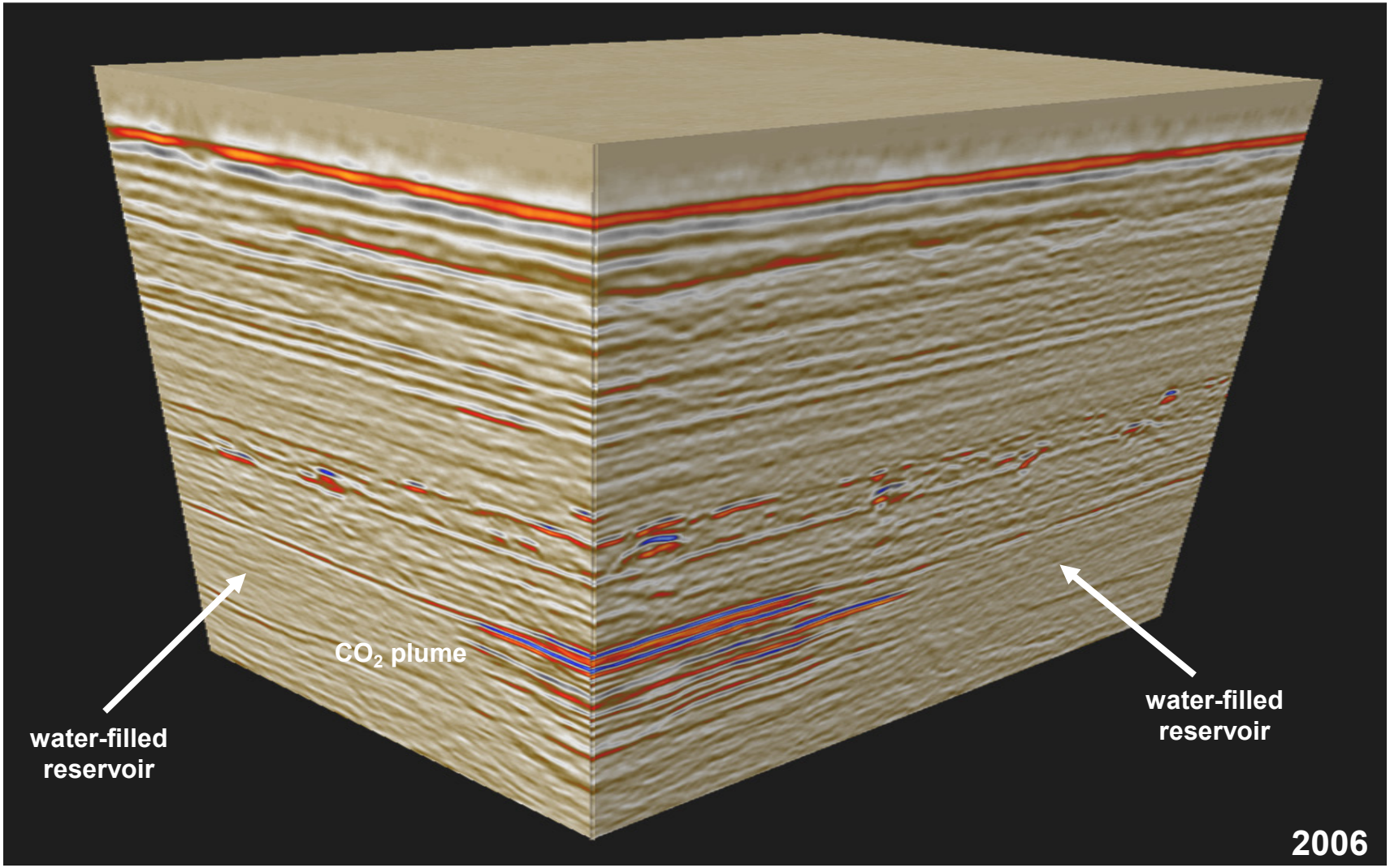
P_{IP} = downhole pressure at the injection point (depth Z)

P_{WH} = wellhead pressure (measured)

g = acceleration due to gravity

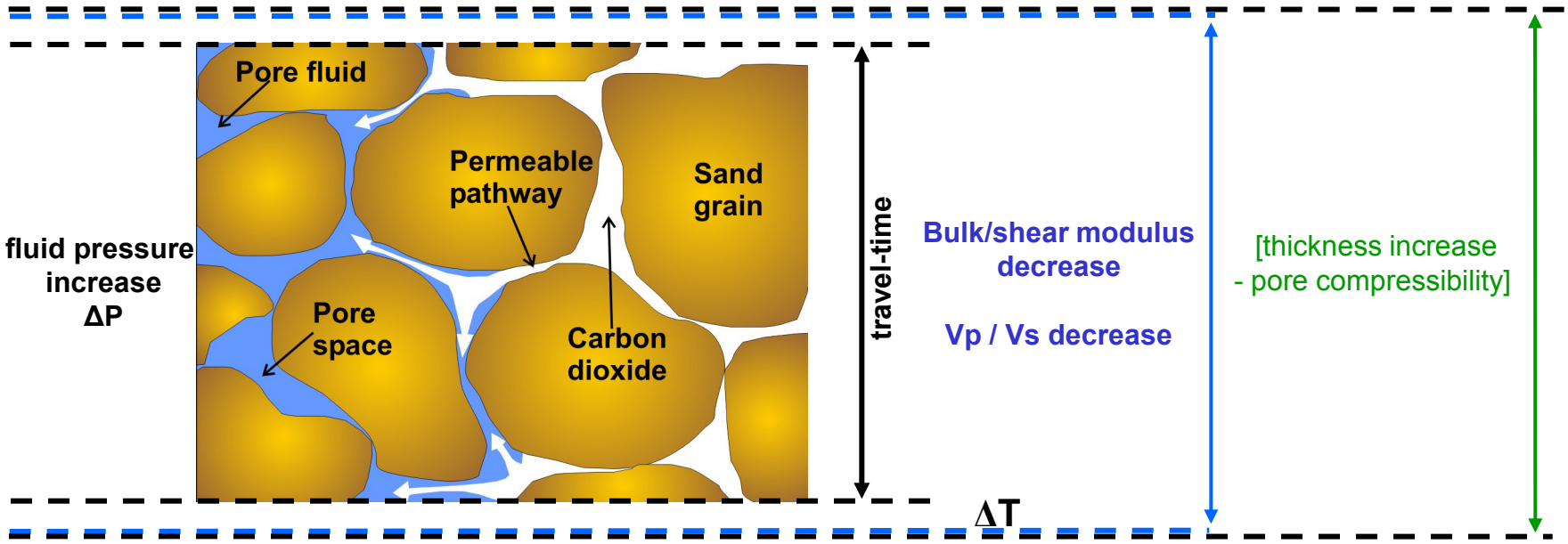
$\rho(z)$ = density of the injected CO_2 in the wellbore at depth z

Sleipner 3D time-lapse seismic



3D continuous coverage of plume and adjacent reservoir (20 km^2)

Seismic pressure response of a clastic reservoir



Empirical – laboratory relationships:

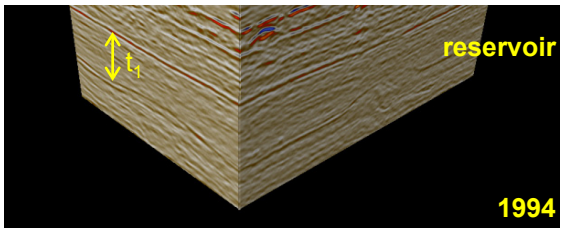
$$V_p = 5.77 - 6.94\phi - 1.73\sqrt{C} + 0.446\left(P_e - e^{-16.7P_e}\right)$$

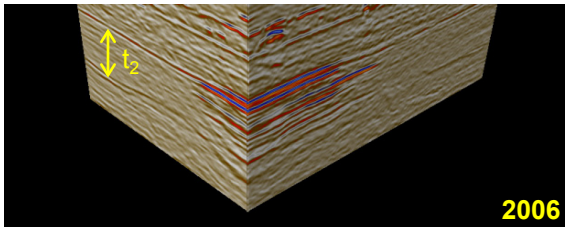
$$V_s = 3.70 - 4.94\phi - 1.57\sqrt{C} + 0.361\left(P_e - e^{-16.7P_e}\right)$$

[Eberhart – Phillips et al 1989 ……porosity, shale content, effective stress]

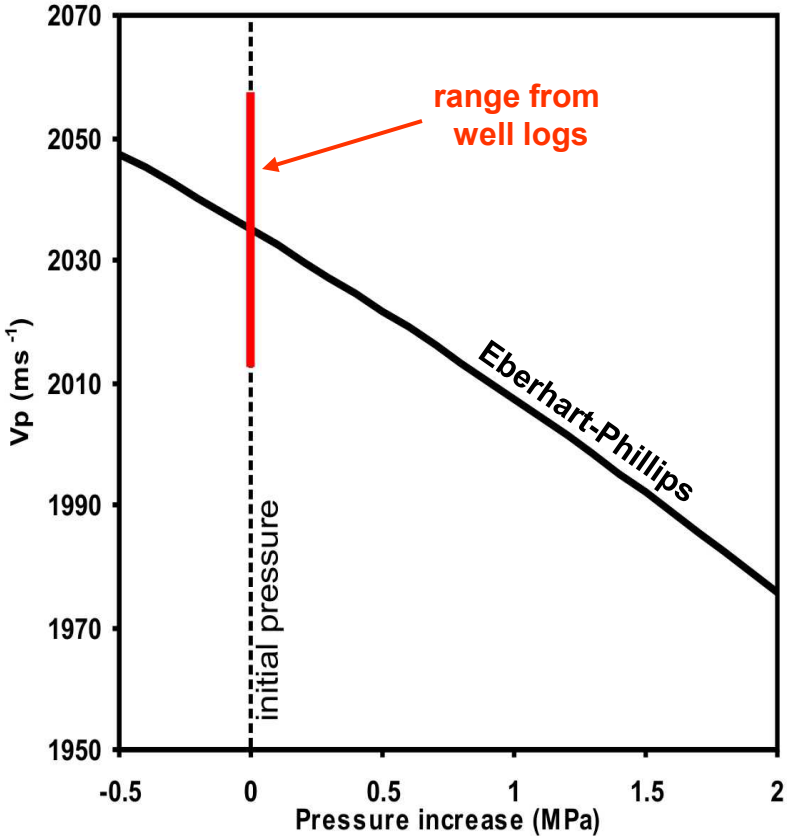
For rocks on normal compaction trend *in situ* effective stress is likely reliable indicator of elastic properties

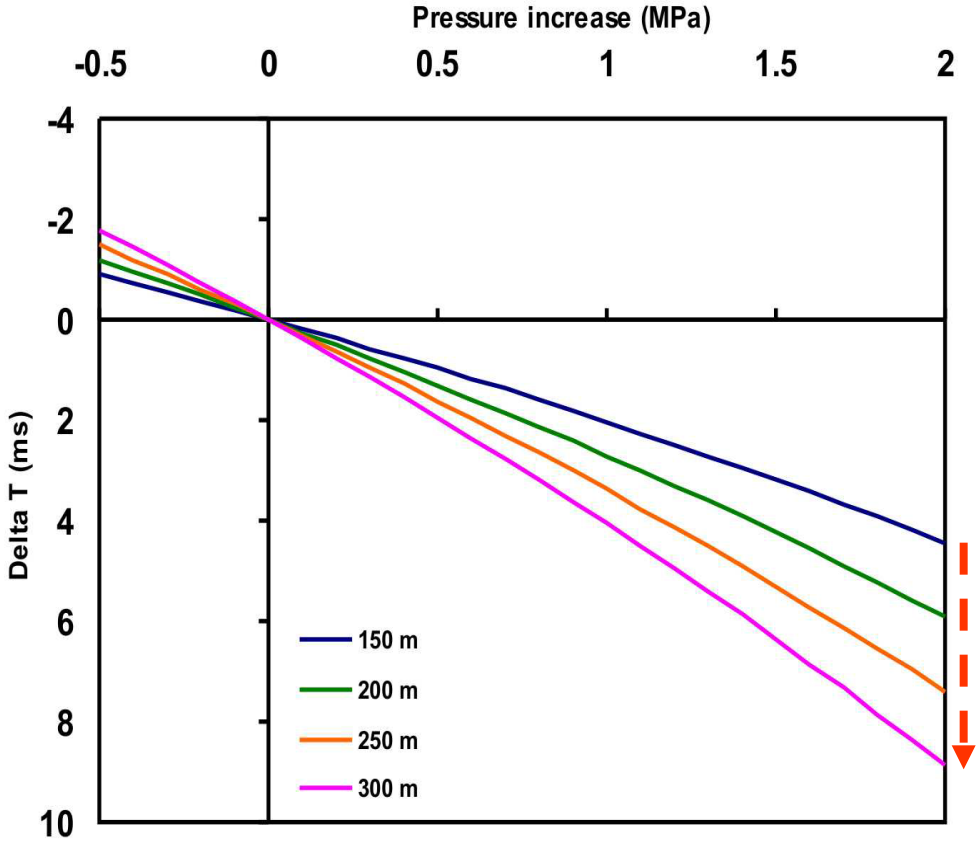
Seismic pressure response (ΔT) of the Utsira Sand





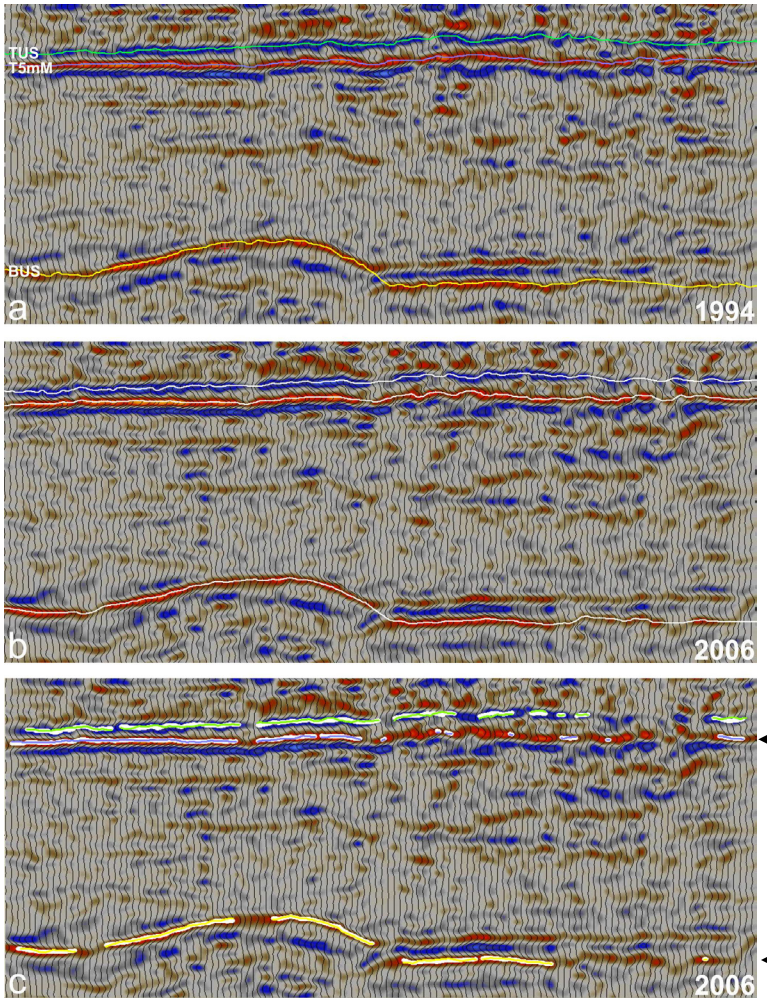
$\Delta T = t_2 - t_1$

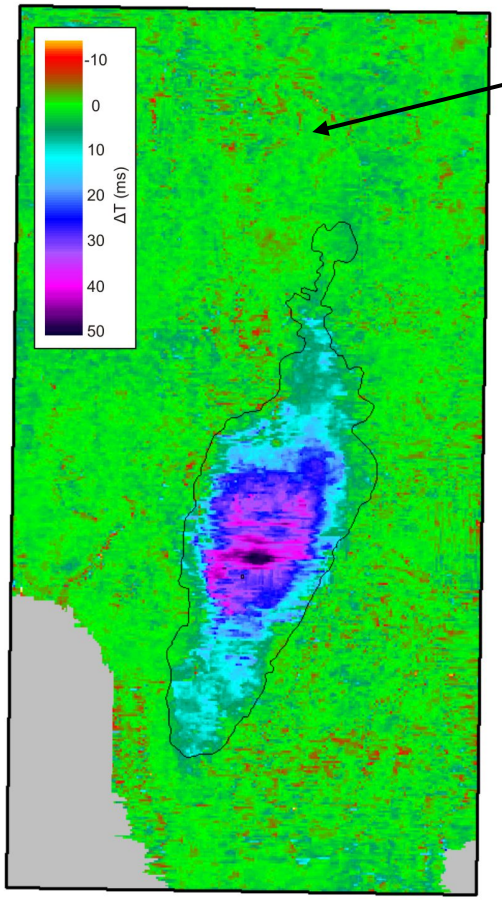




10 bars ~ 3 - 4 ms

Measuring ΔT in the Utsira Sand



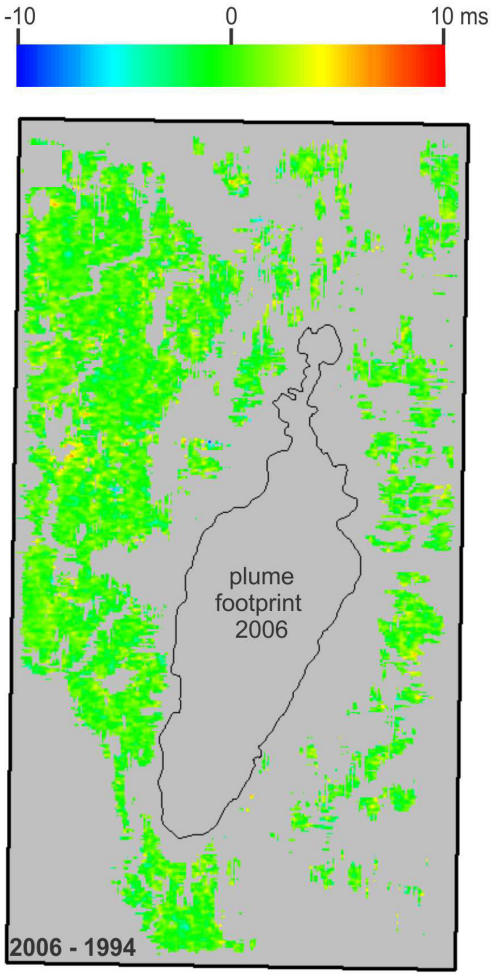


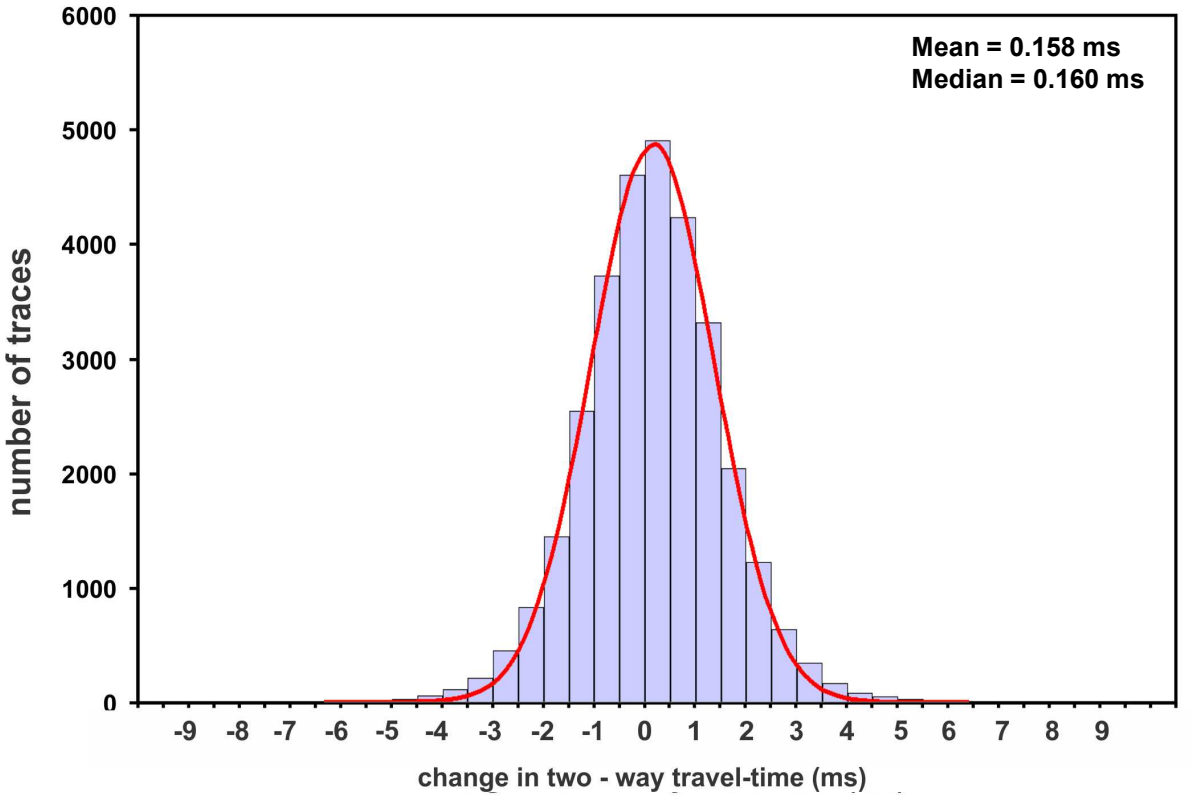
Repeatability mismatches (noise)

ΔT 2006 – 1994

For noise-free data, travel-time resolution for a single trace ~ 0.5 ms
>116500 traces
> 30000 high quality traces

Measured ΔT 1994 to 2006 (T5mM to BUS)



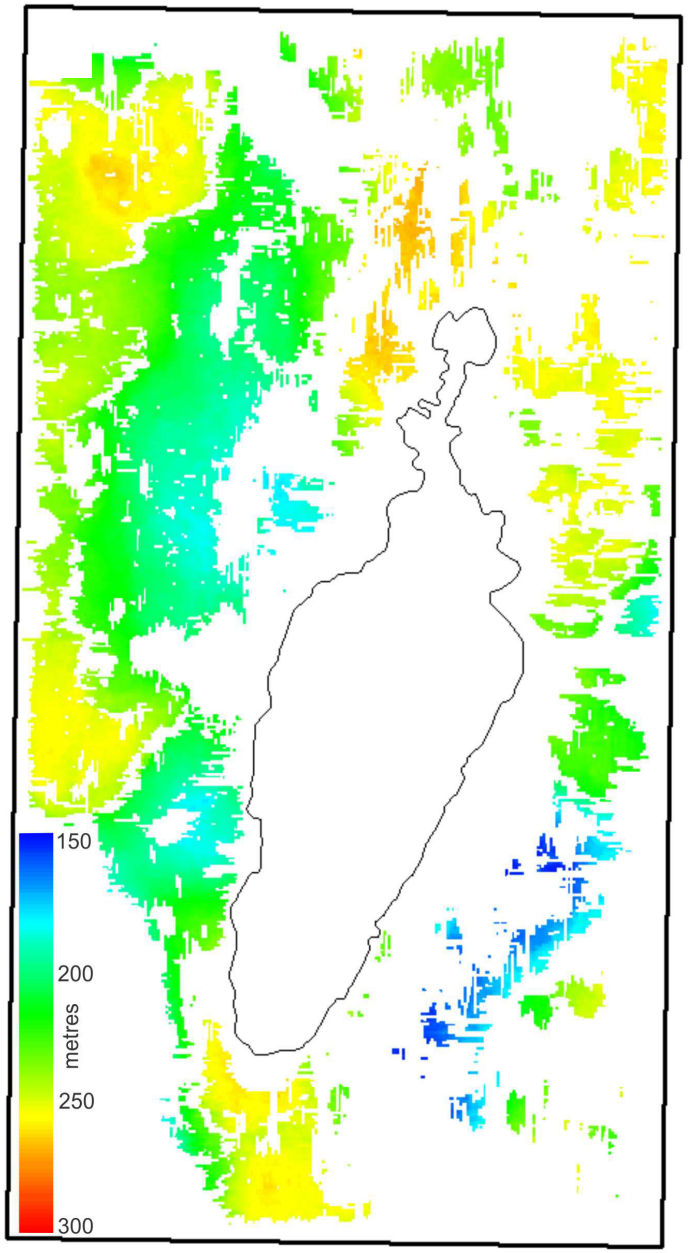


31138 high quality traces

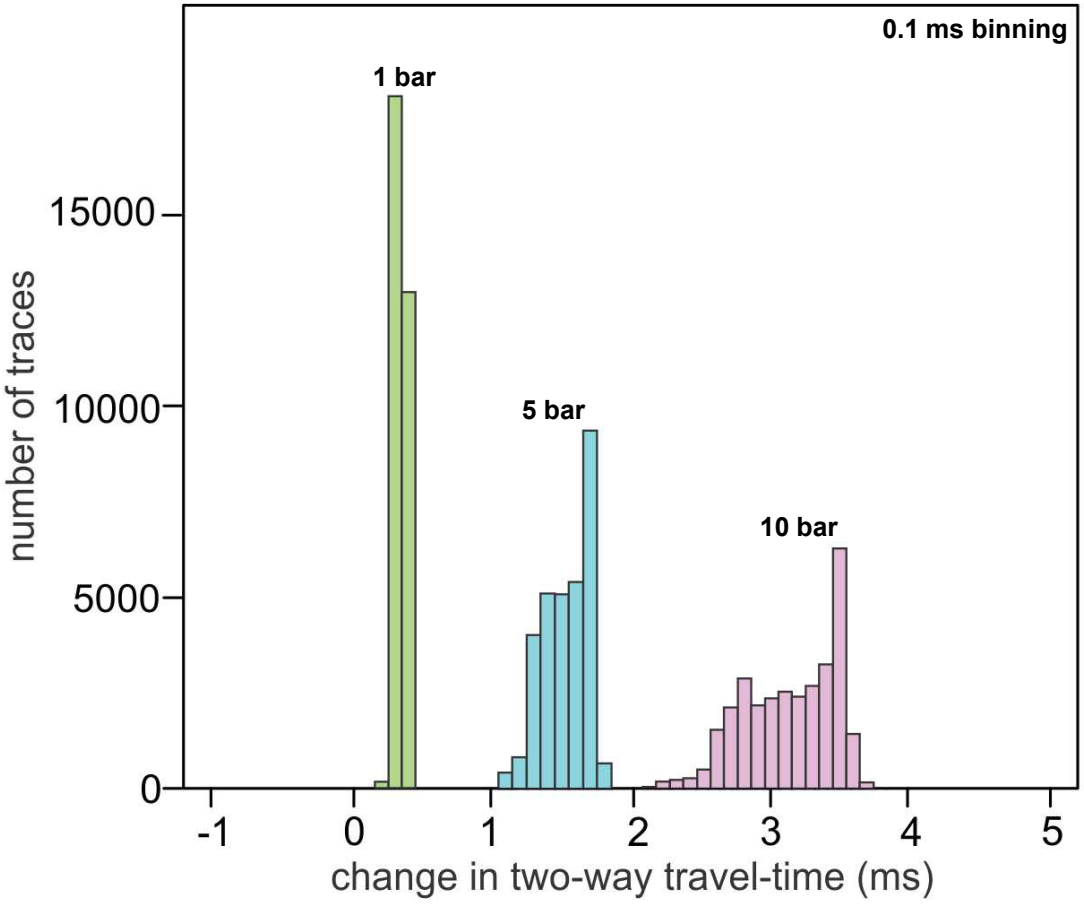
Random trace-to-trace travel-time ‘jitter’ due to differences in ambient noise and acquisition geometries on successive surveys – subset of the time-lapse ‘repeatability noise’

Systematic (DC) time-lapse timeshifts cancelled

Calculated noise-free ΔT 1994 to 2006 (T5mM to BUS)

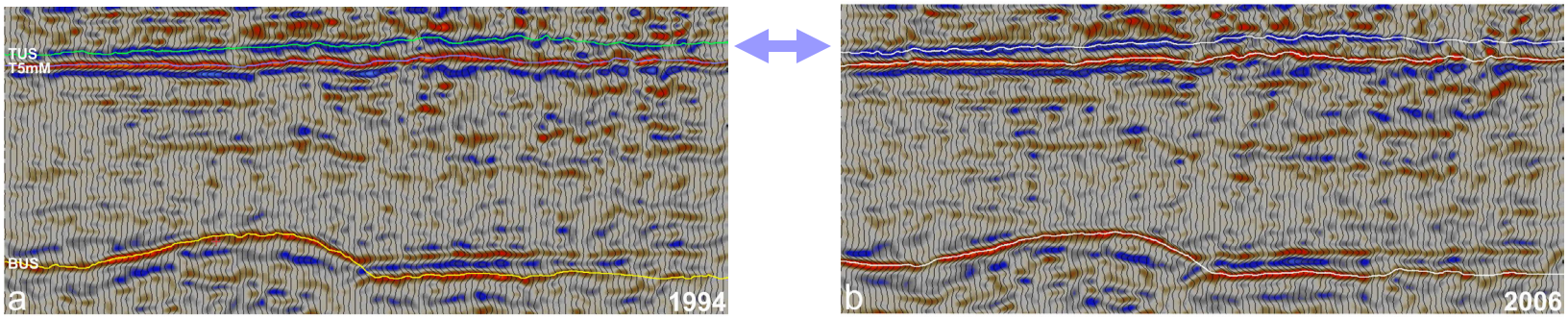


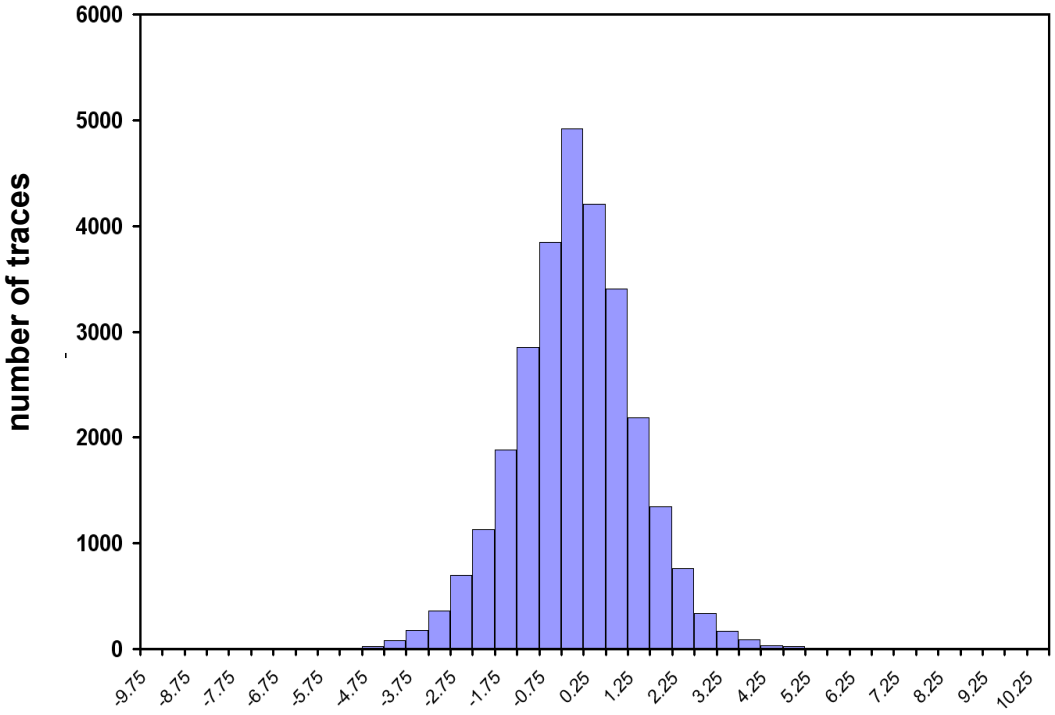
reservoir thickness



Top reservoir repeatability noise

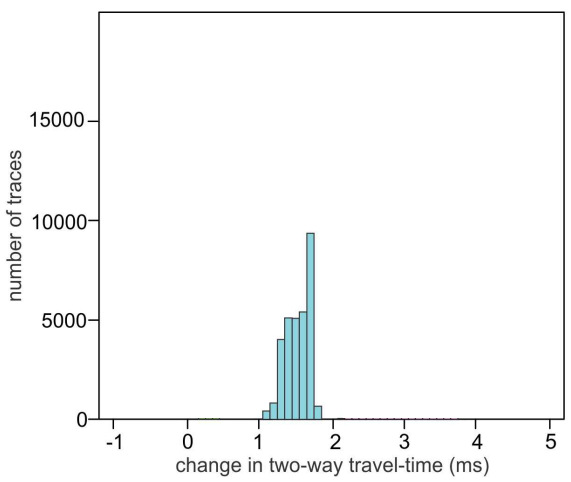
– how well is a single horizon reproduced on successive surveys?



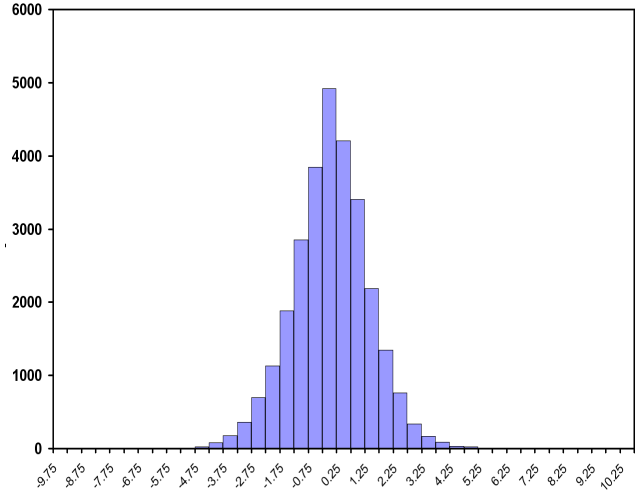


Measured ΔT at top reservoir (i.e. on a single horizon)

Calculating the reservoir response

reservoir ΔT response = 

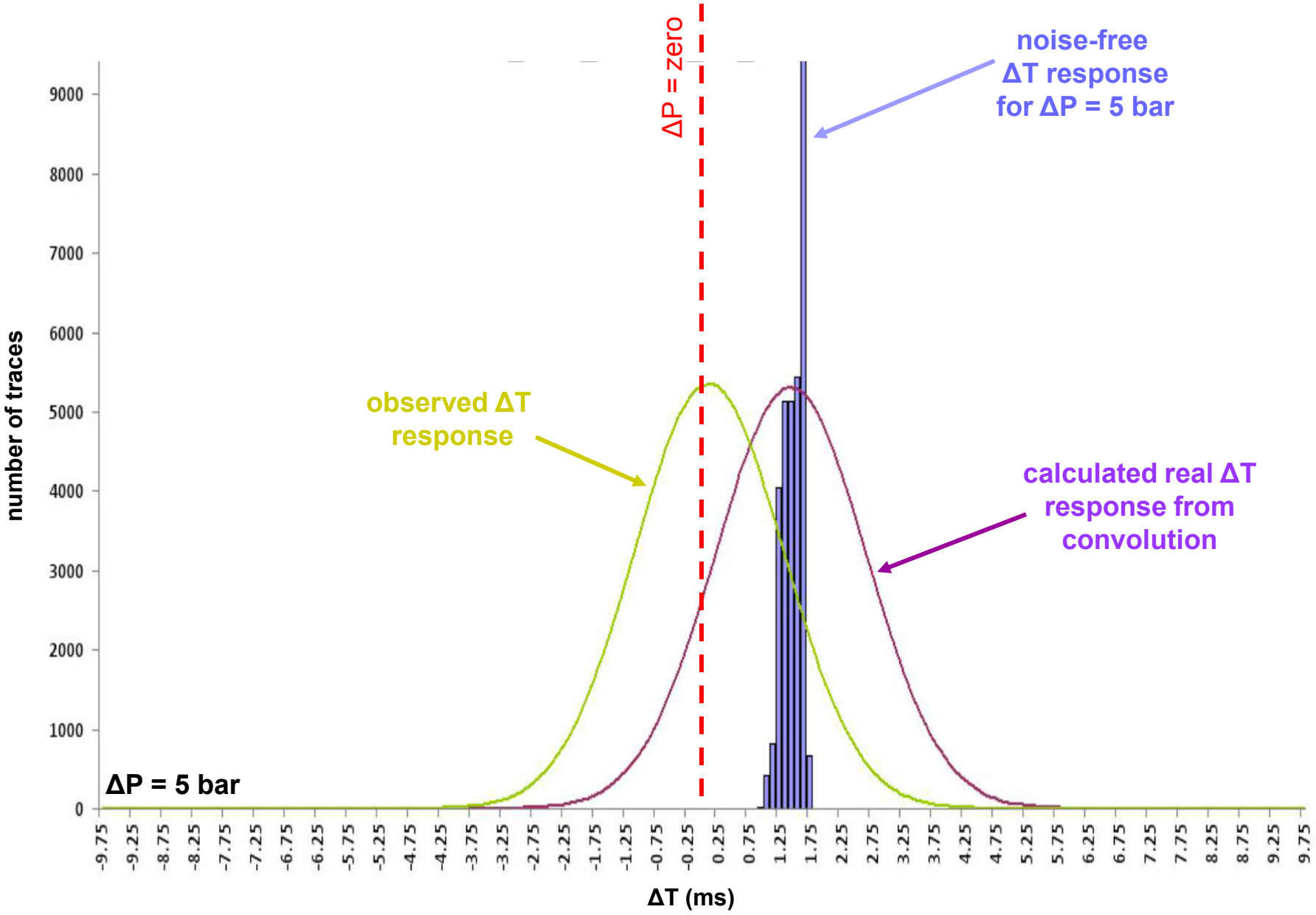
noise - free reservoir response

* 

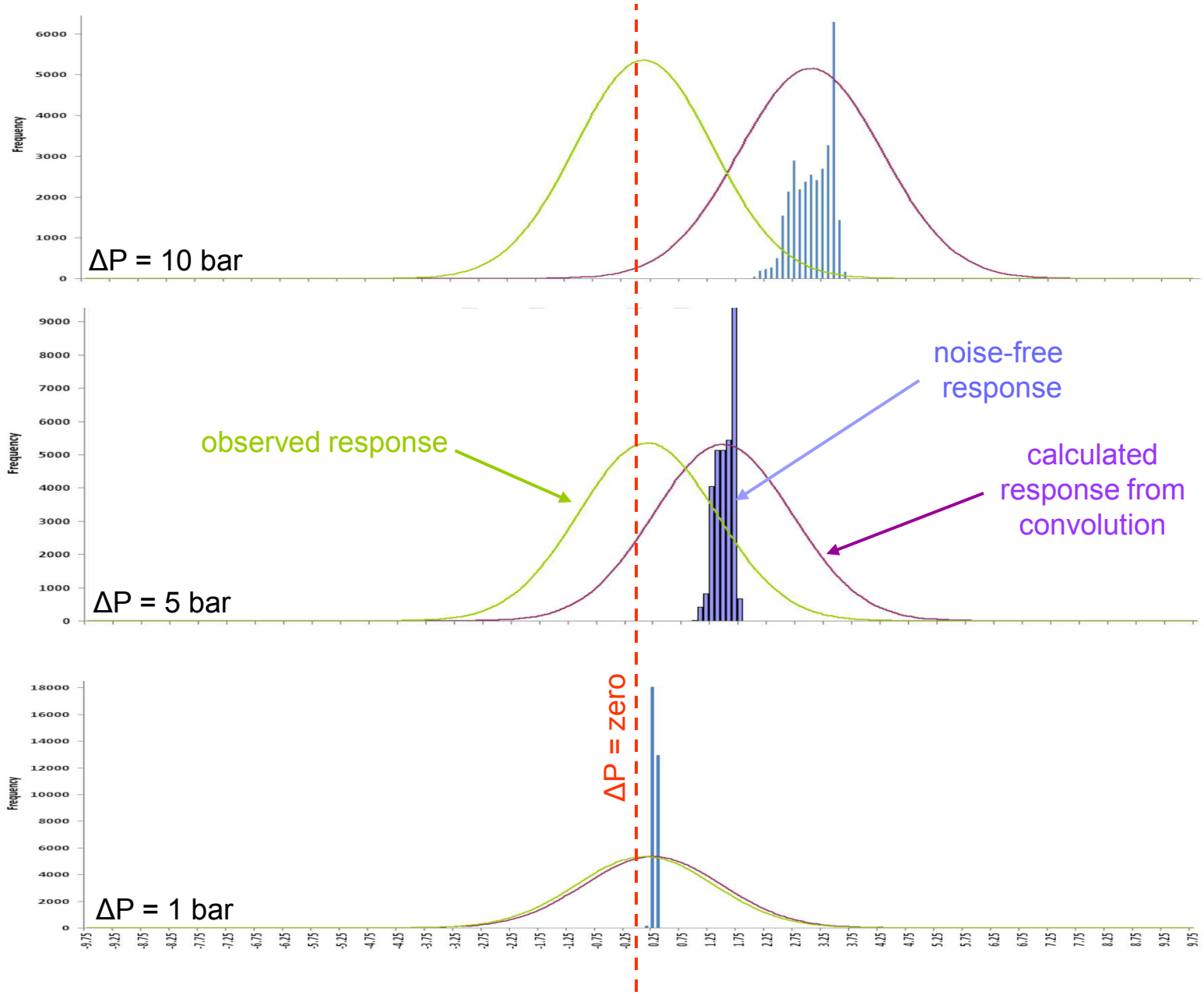
repeatability noise distribution

time-series convolution

Calculated ΔT 1994 to 2006 from convolution (T5mM to BUS)



Calculated ΔT 1994 to 2006 from convolution (T5mM to BUS)



Conclusions

Observed travel-time changes (ΔT) 2 – 5 km from IP show scatter with normal distributions about very small mean/median values < 1 ms

Seismically-determined pressure change for 1994 to 2006
ΔP << 5 bars
ΔP < 1 bar

Open aquifer or boundary at the aquifer limits

No evidence of internal flow compartmentalisation

Acknowledgements

CO2 REMOVE
research monitoring verification

BIGCCS
International CCS Research Centre

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH