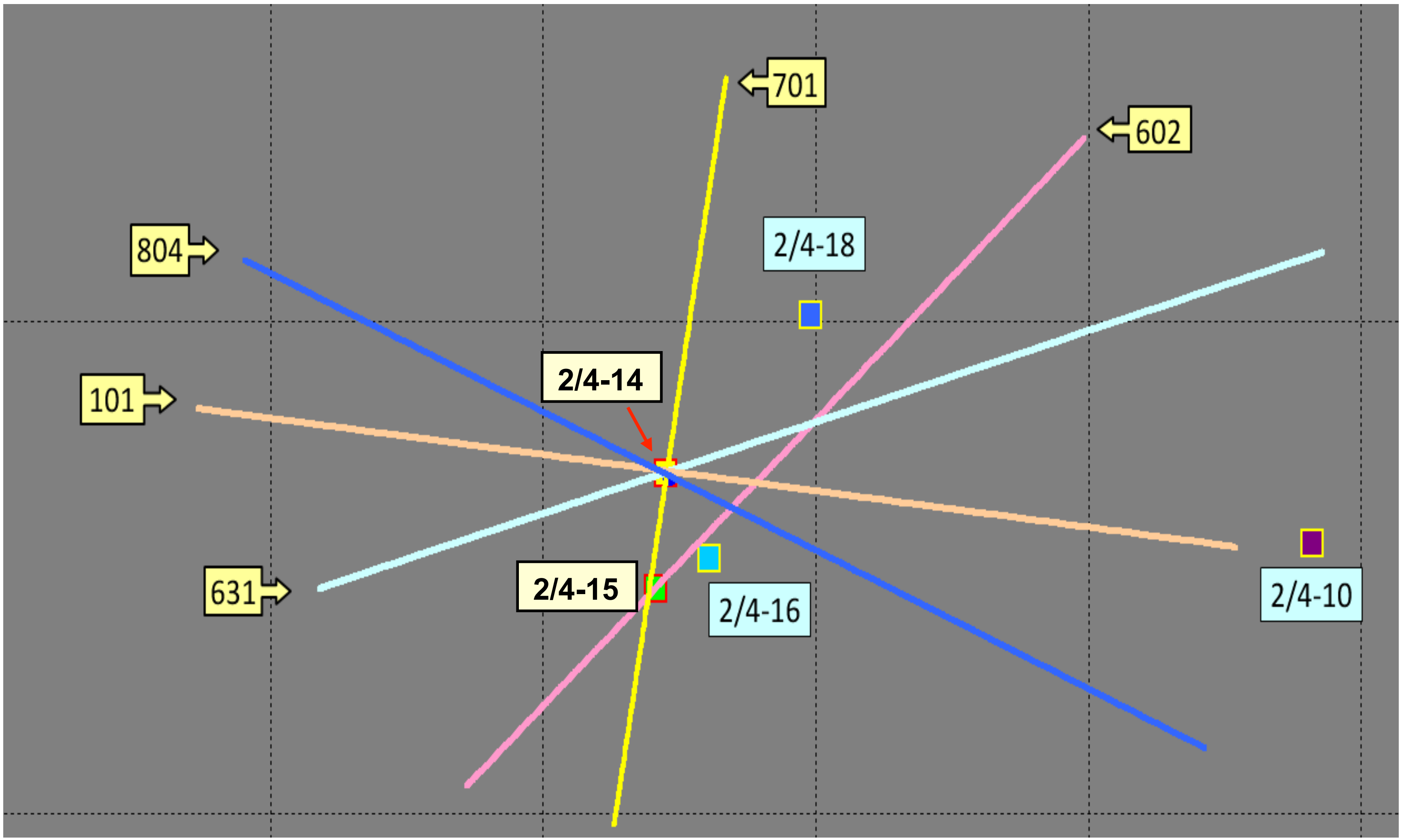
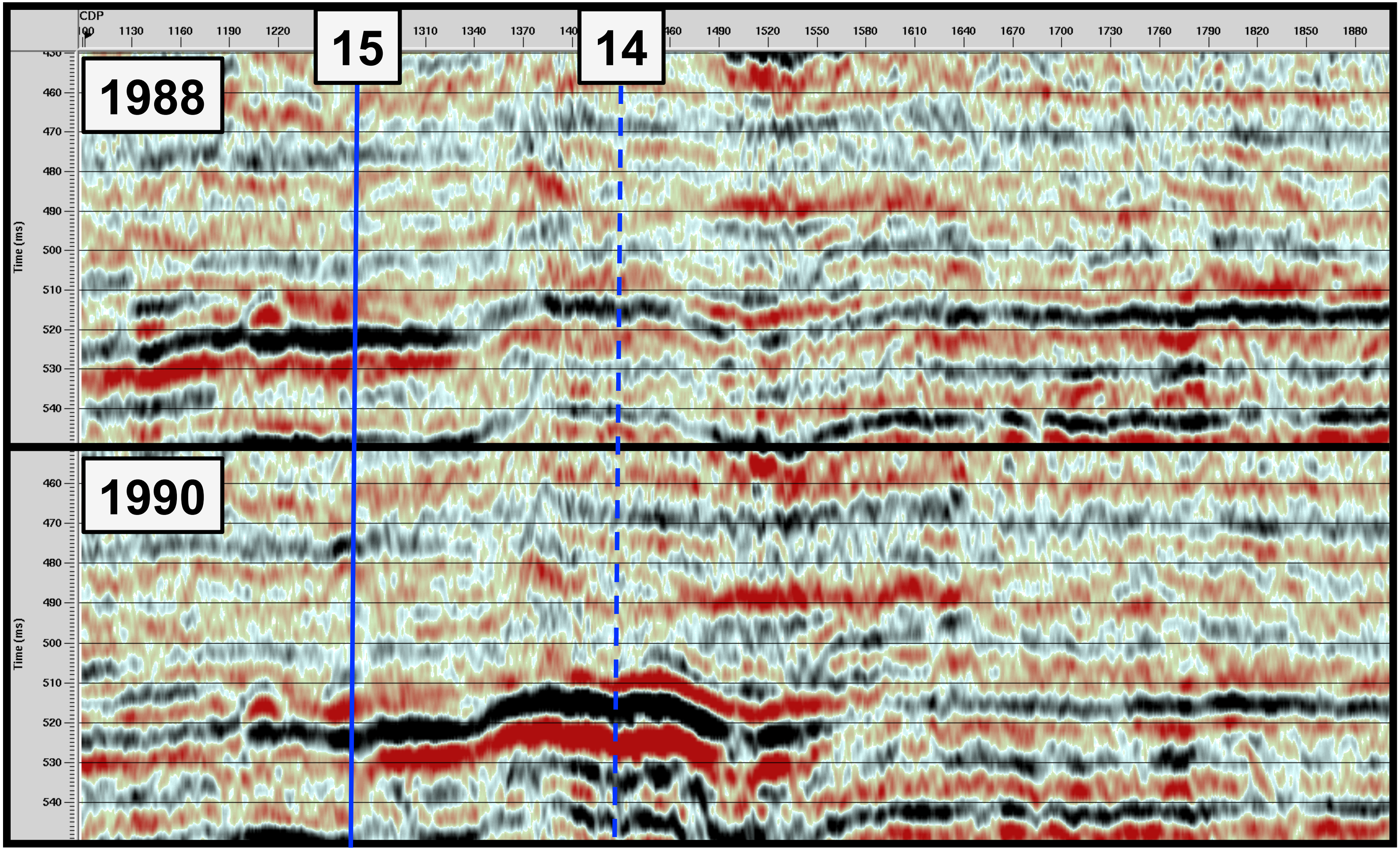
Estimating pressure and saturation changes from 4D traveltime shifts and a simple pseudo steady state flow equation

Martin Landrø, NTNU

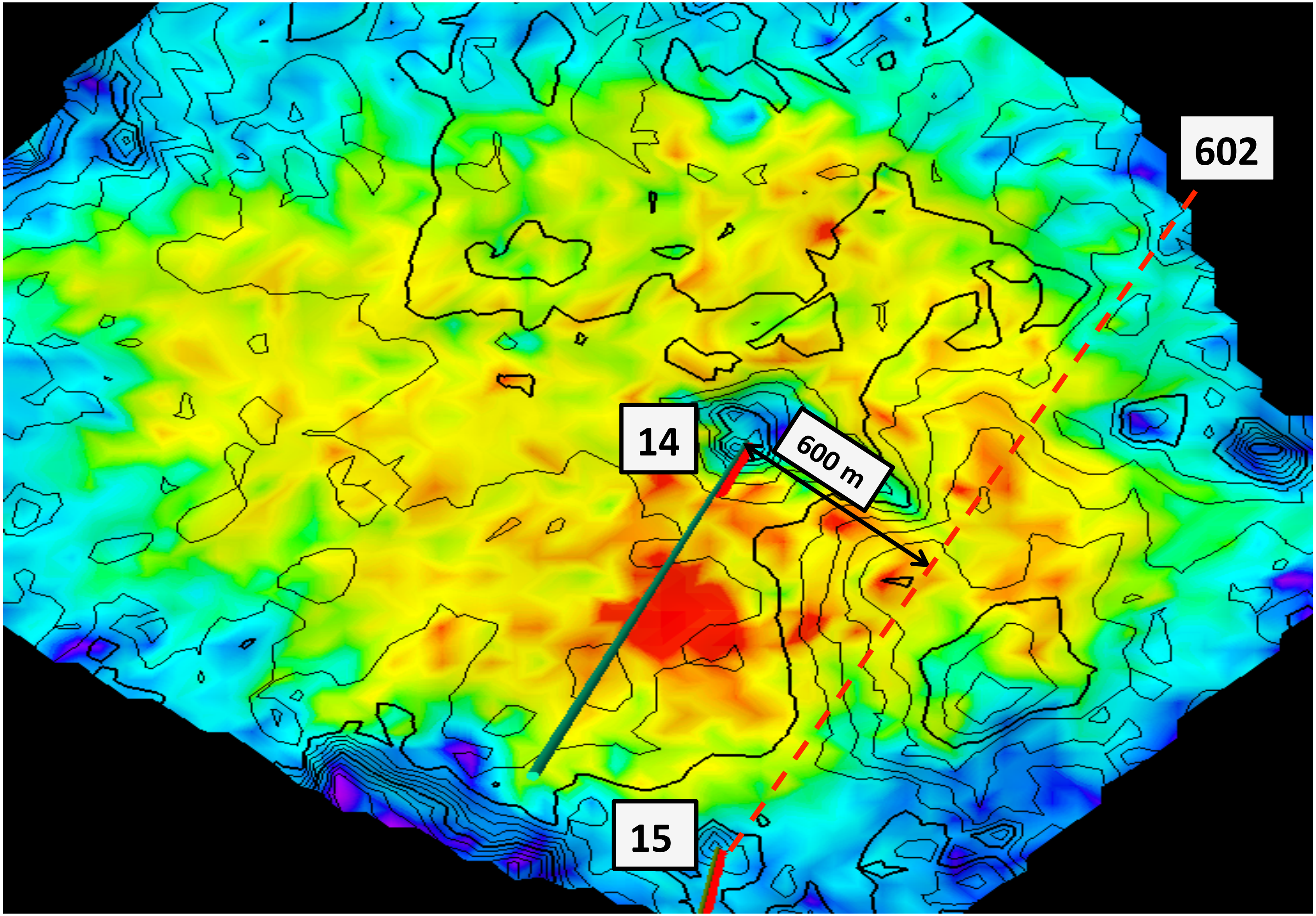
Location of the 602 line: 600 m away from the 14-well



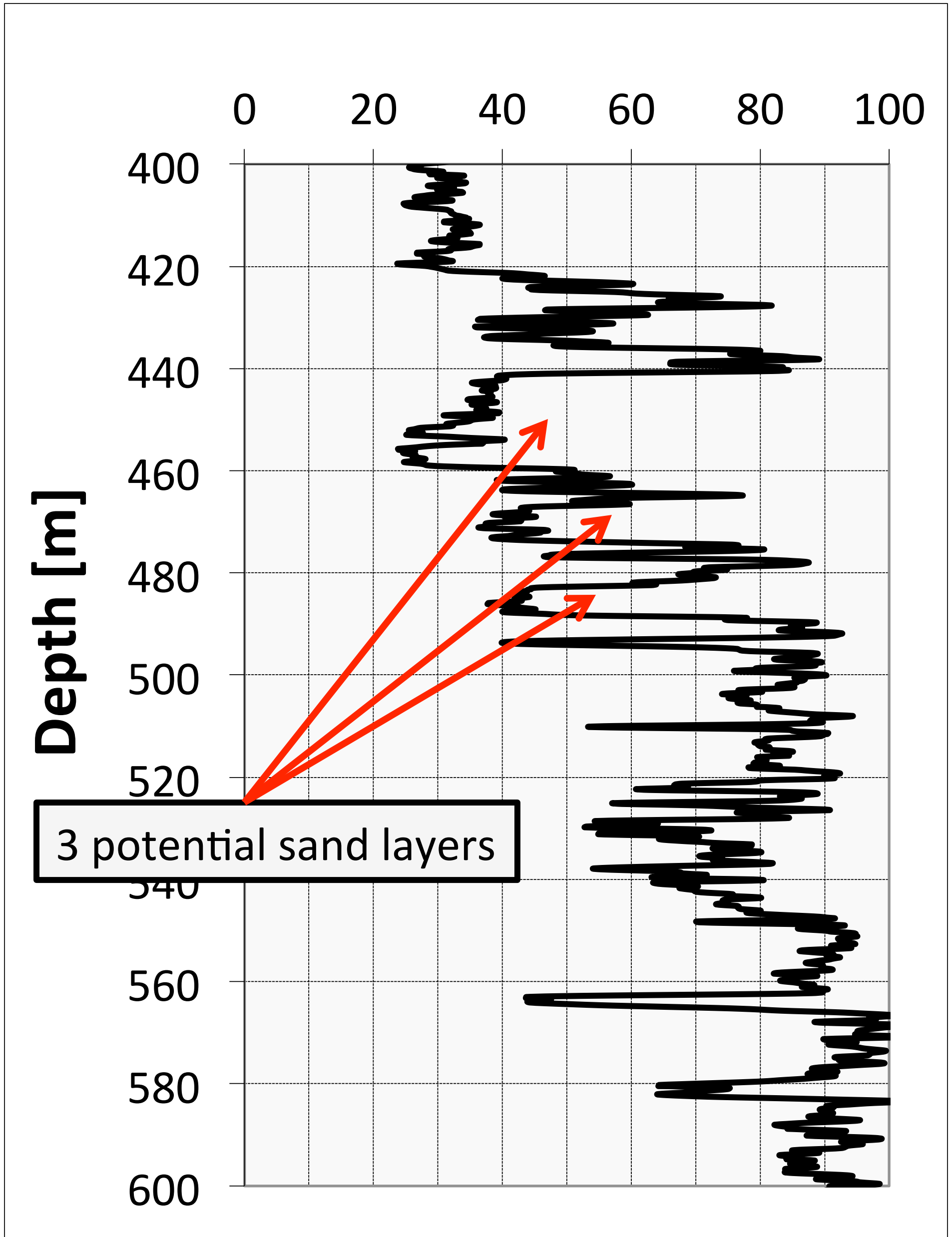
Line 602 – amplitude increase at 490 m sand

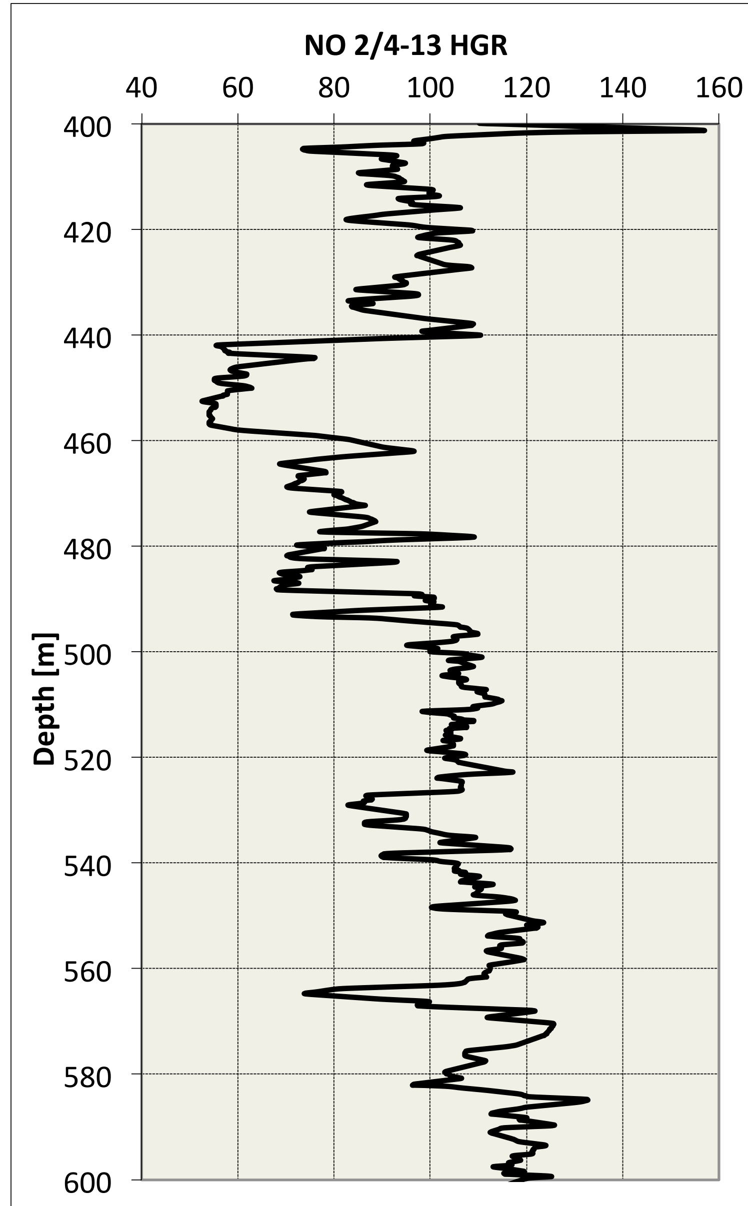


Amplitude map of the top sand – 1991
602 line is 600 m away from the 14-well

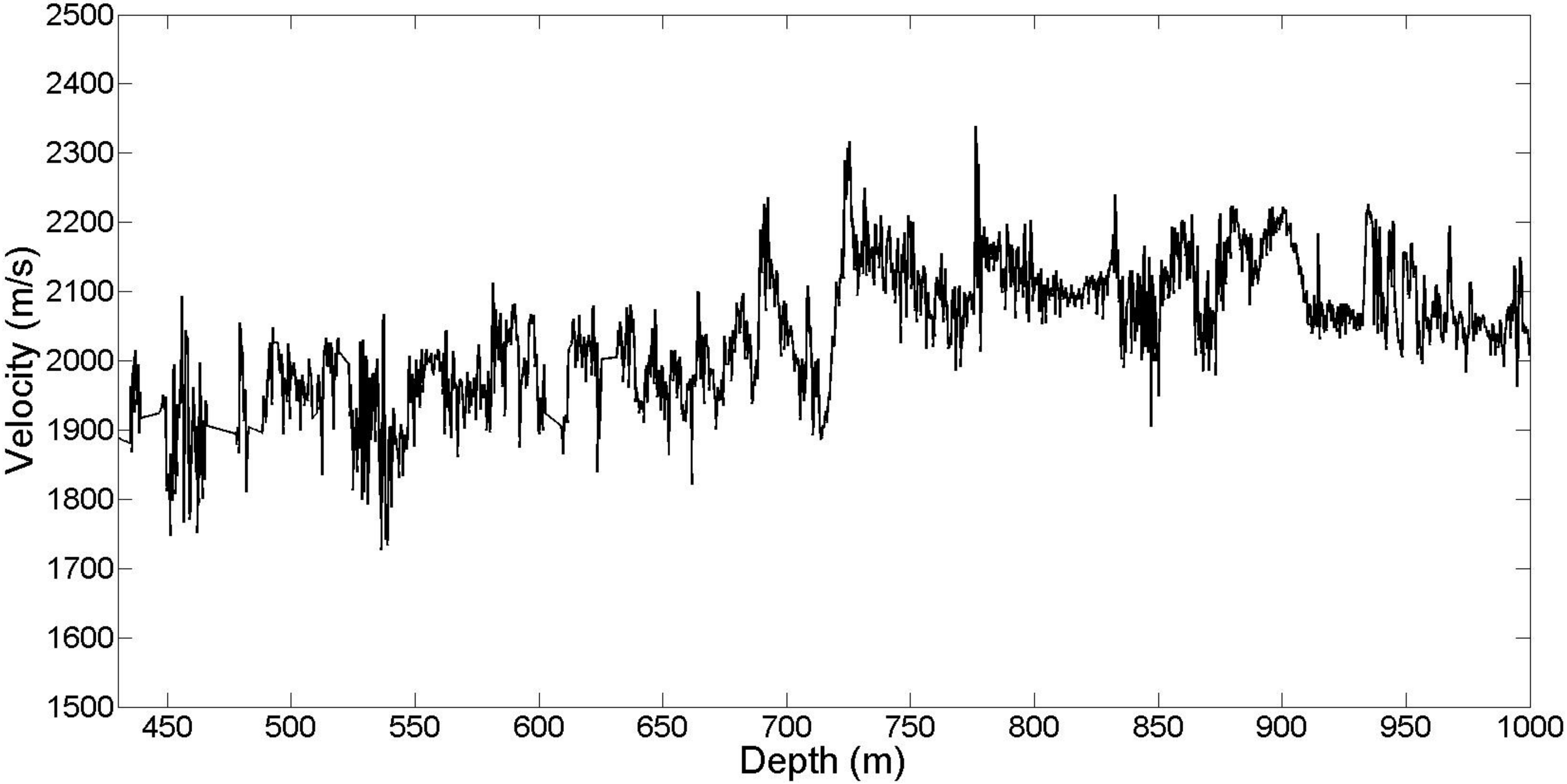


Gammalogs; wells 16 and 13 (800 m apart)



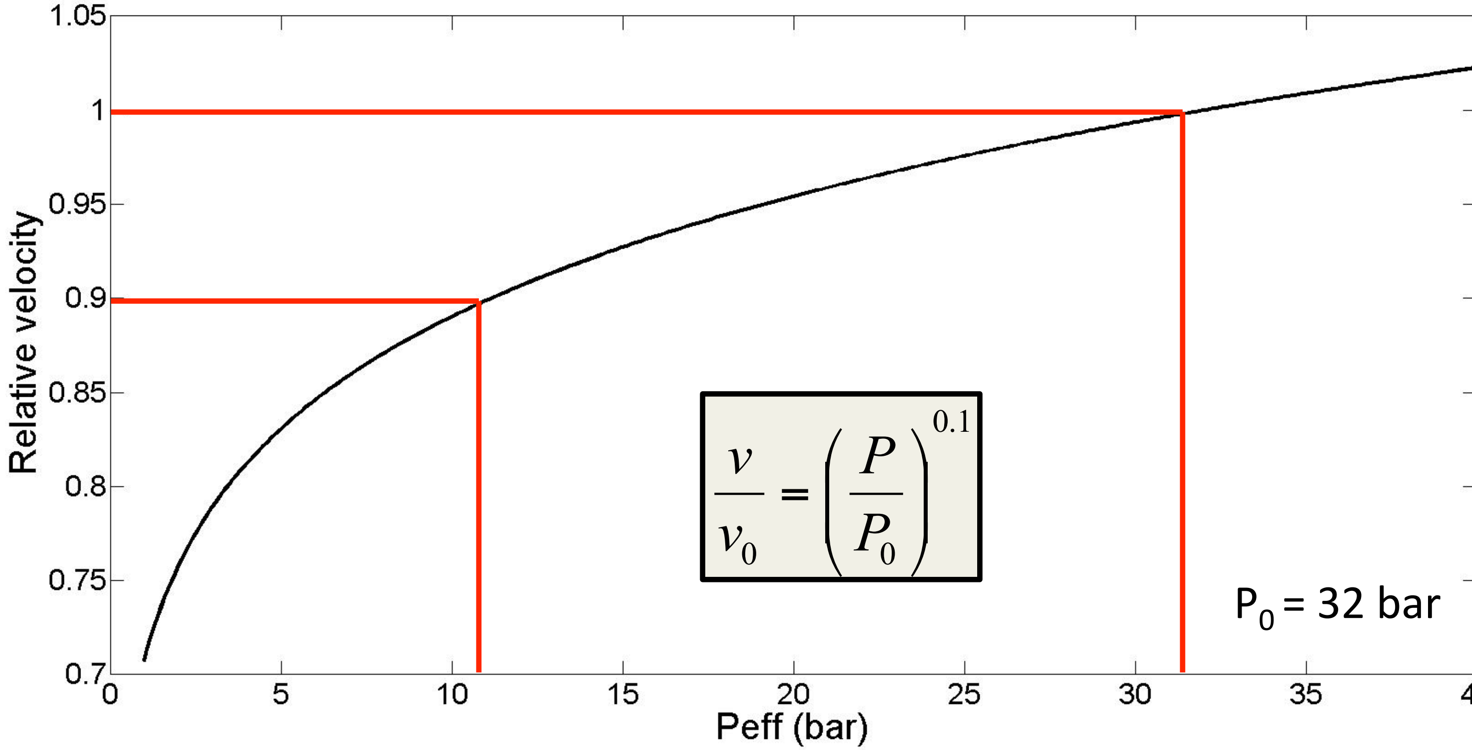


P-wave velocity in the 16-well, 800 m away from the 14-well – close to the 602-line



V = 1950 m/s between 450 and 500 m

Relative velocity versus effective pressure

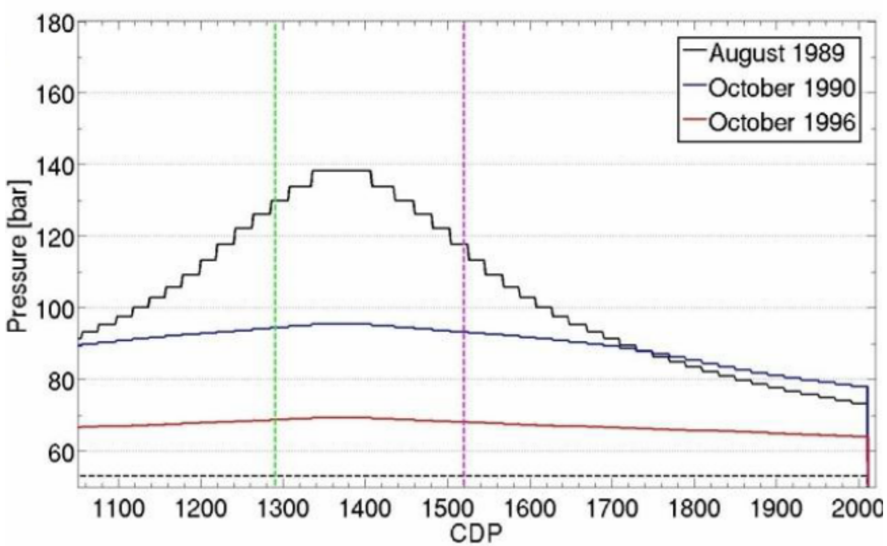


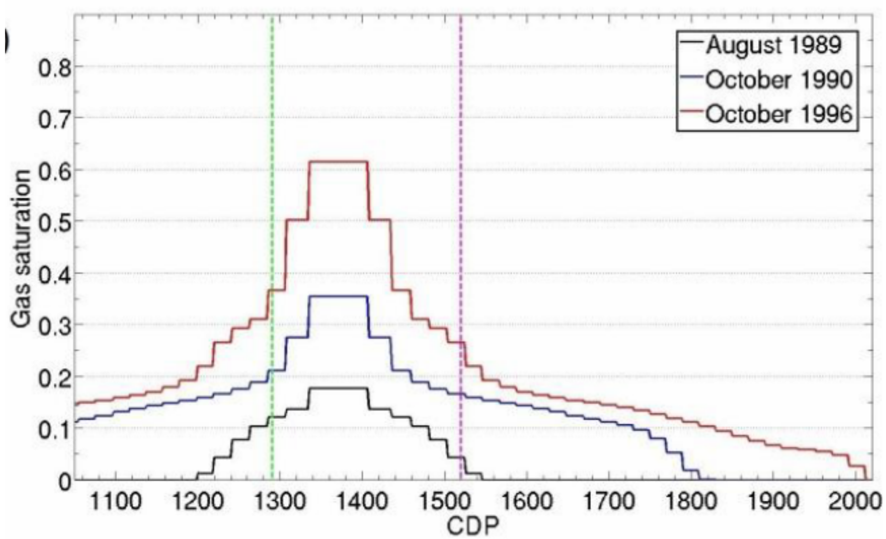
A reduction in effective pressure of 21 bar => 10 % reduction in P-wave velocity

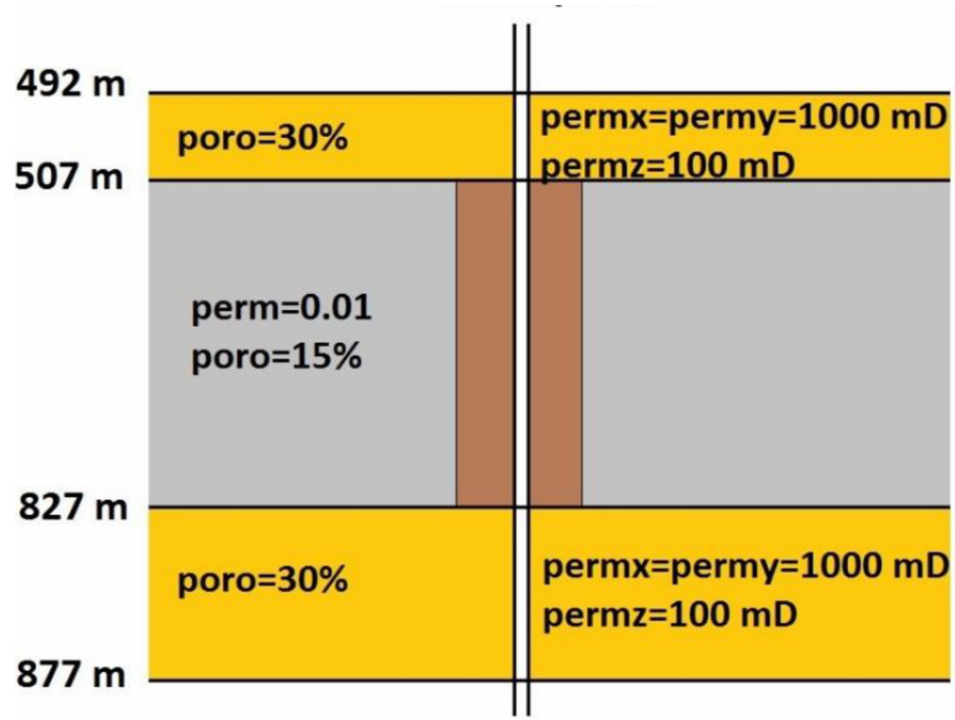
For a 20 m sand, this corresponds to a time shift of 1.1 ms

A pore pressure increase of 10 bar => 0.4 ms timeshift, and 20 bar => 1 ms

Comparing with reservoir simulation – upper sand layer
MSc thesis of Eli Langseth







Pseudo steady state flow: No cross-flow boundary conditions

$$p(r) = p_w - \frac{qB\mu}{2\pi hk}\left(\ln\frac{r}{r_w} - \frac{r^2}{2r_e^2}\right)$$

Eq. 13.33 in Zolotukhin and Ursin, 2000

P_w = well pressure
R_w = well radius

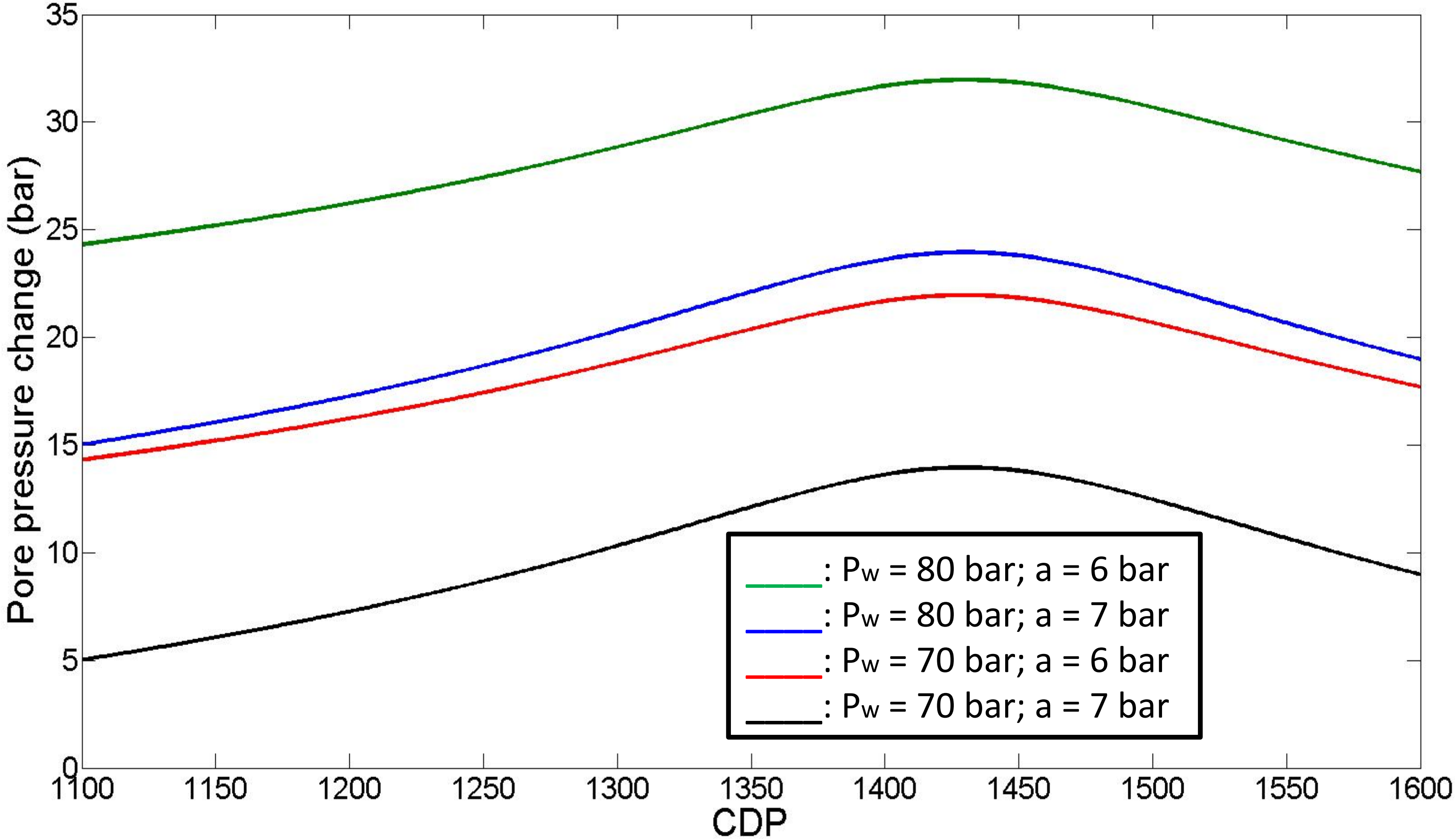
Assume that r_e is large =>

$$p \approx p_w - a\ln\left(\frac{r}{r_w}\right)$$

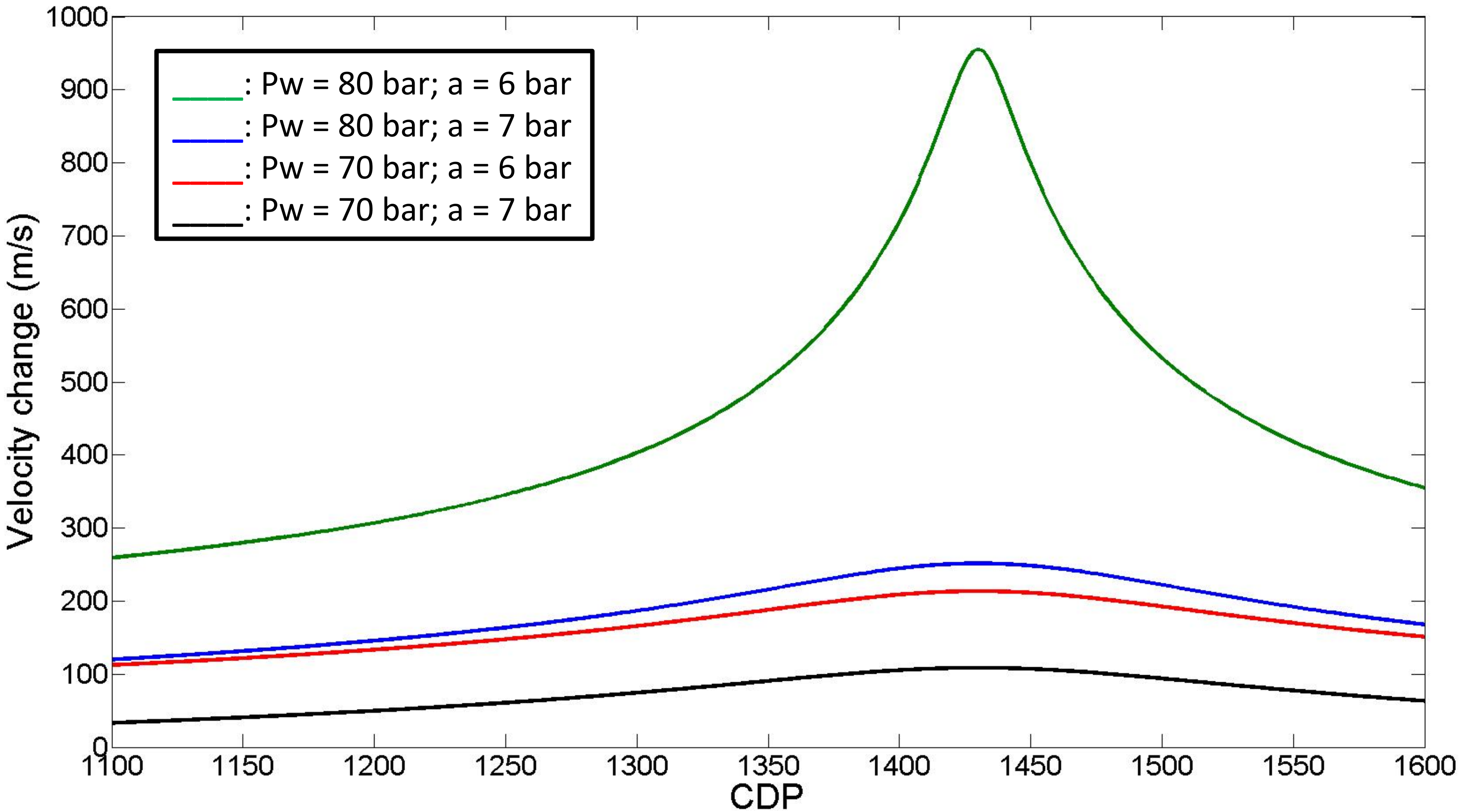
Pressure decrease around the blowing well

We will use p_w and a as inversion parameters

Pressure for line 602 using $p \approx p_w - a \ln\left(\frac{r}{r_w}\right)$ and R_w= 0.2 m

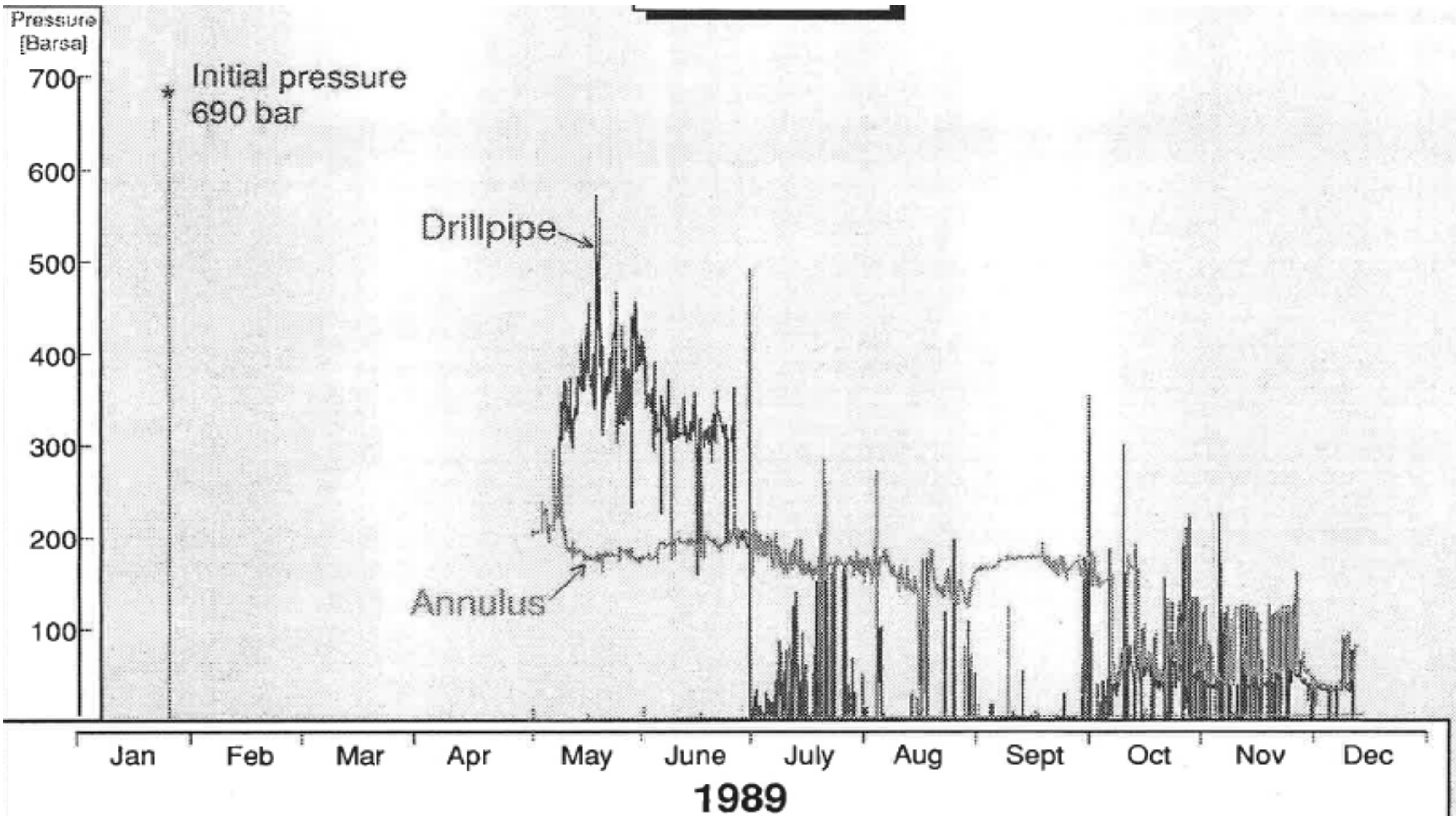


Velocity changes using $p \approx p_w - a \ln\left(\frac{r}{r_w}\right)$ and $v \approx v_0 \left(1 - \frac{p}{p_0}\right)^{\gamma}$

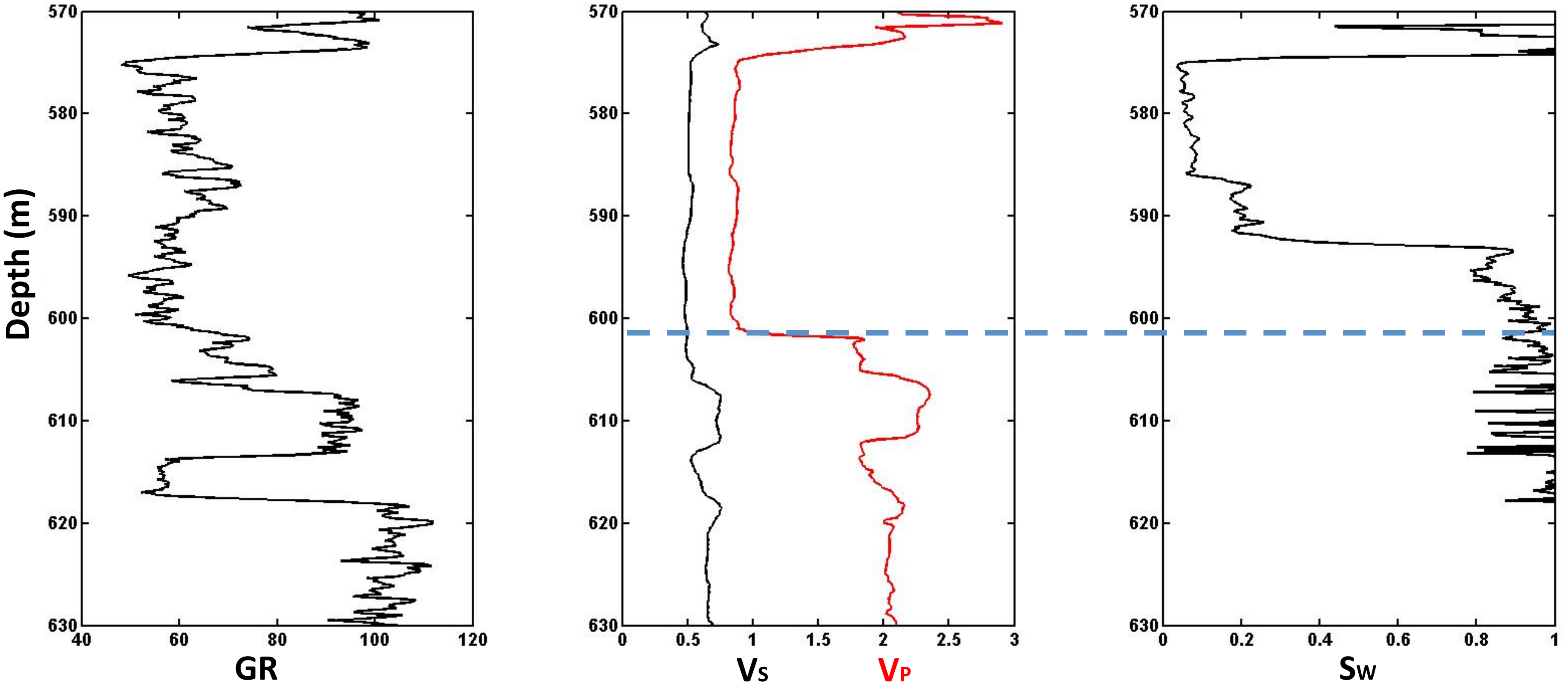


Rw = 0.2 m; p0 = 32 bar and v0 = 1950 m/s

Recorded wellhead pressure 2/4-14



Well logs from Peon field, offshore Norway



Notice: No change in P-wave velocity until Sw = 0.95.

P-wave velocity in gas-filled sand: 850 m/s, porosity ~35%

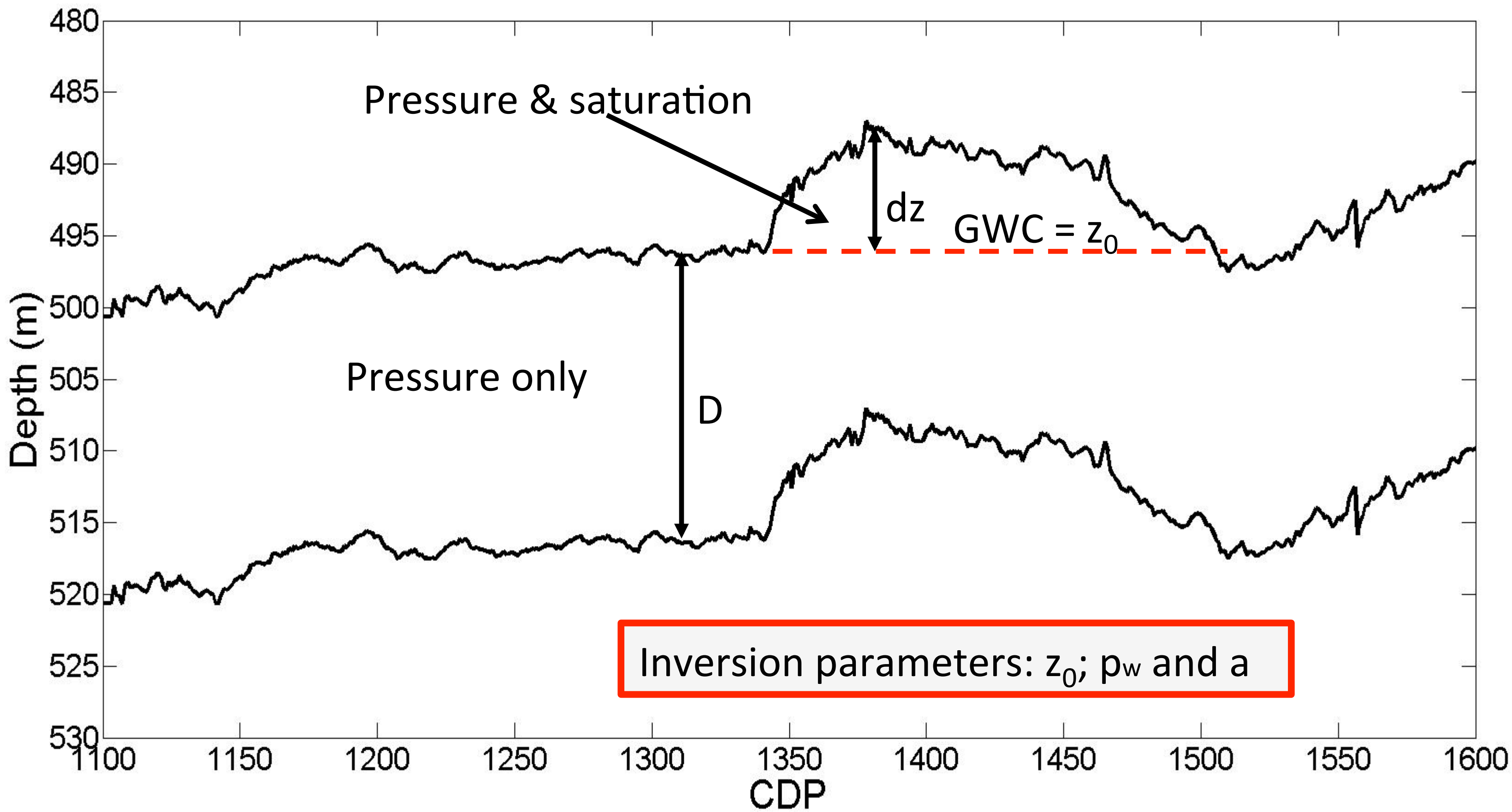
Time shift caused by saturation and pressure changes:

$$\Delta T = dz\,\frac{v_1 - v_2}{v_1 v_2} + D\,\frac{1 - \left(1 - \frac{p}{p_0}\right)^{\gamma}}{v_1\left(1 - \frac{p}{p_0}\right)^{\gamma}}$$

Saturation — Pressure

$$p \approx p_w - a\ln\left(\frac{r}{r_w}\right)$$

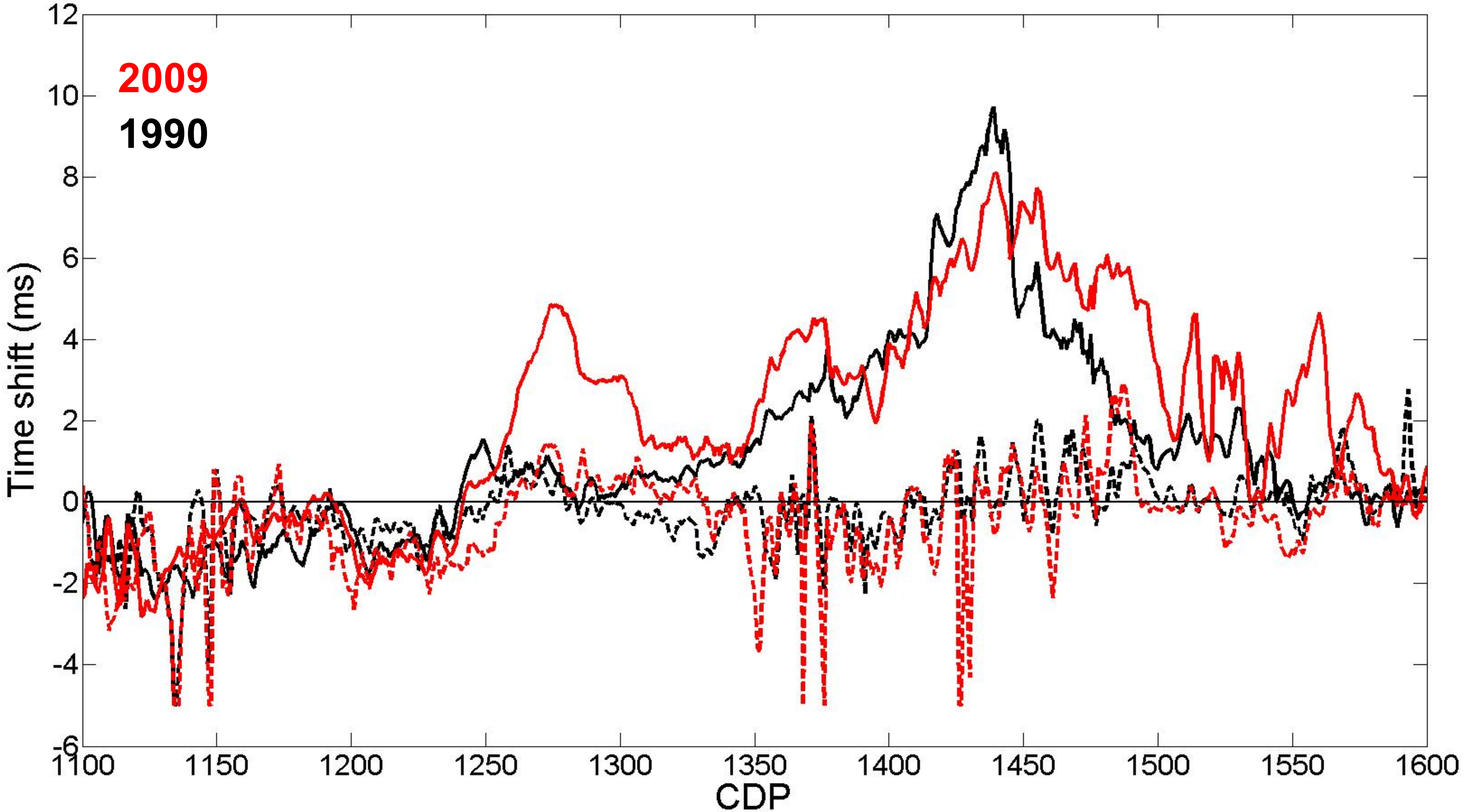
V1 = 1950 m/s
V2 = 850 m/s



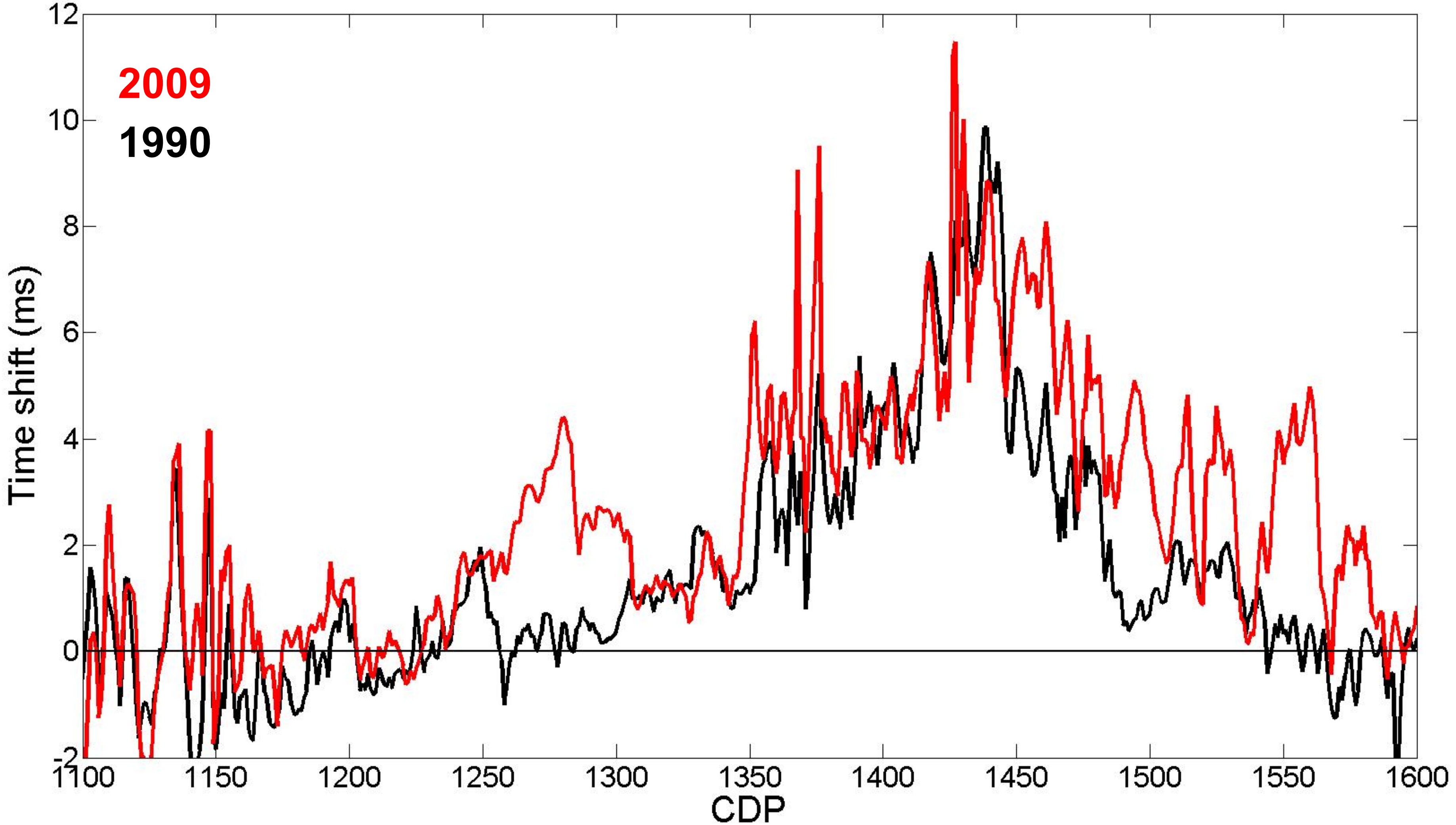
Cross-correlation time shift estimation

Above sand cross-correlation: 430-490 ms (dashed lines)

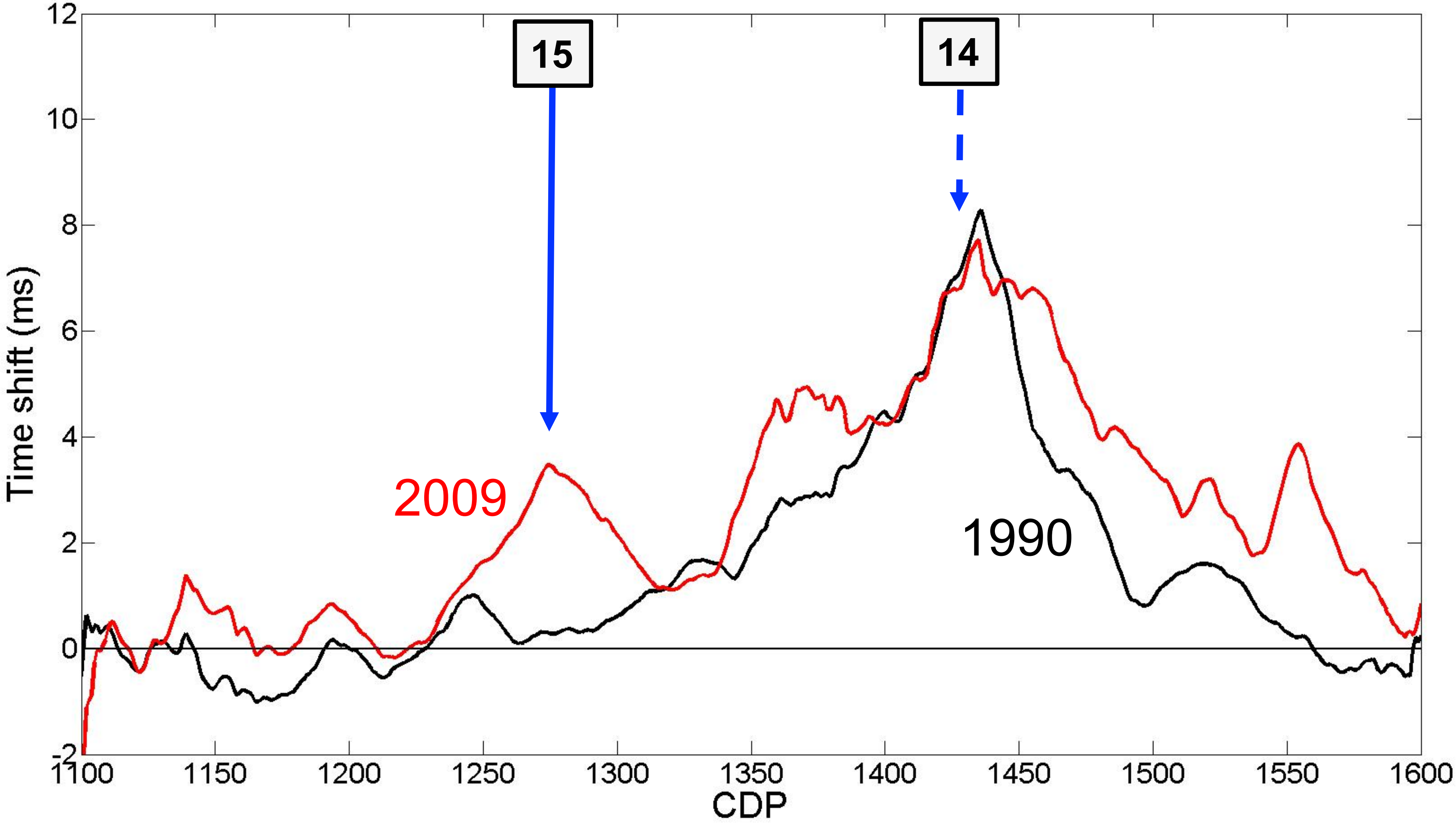
Below sand cross-correlation: 630-690 ms (solid lines)



Estimated time shifts

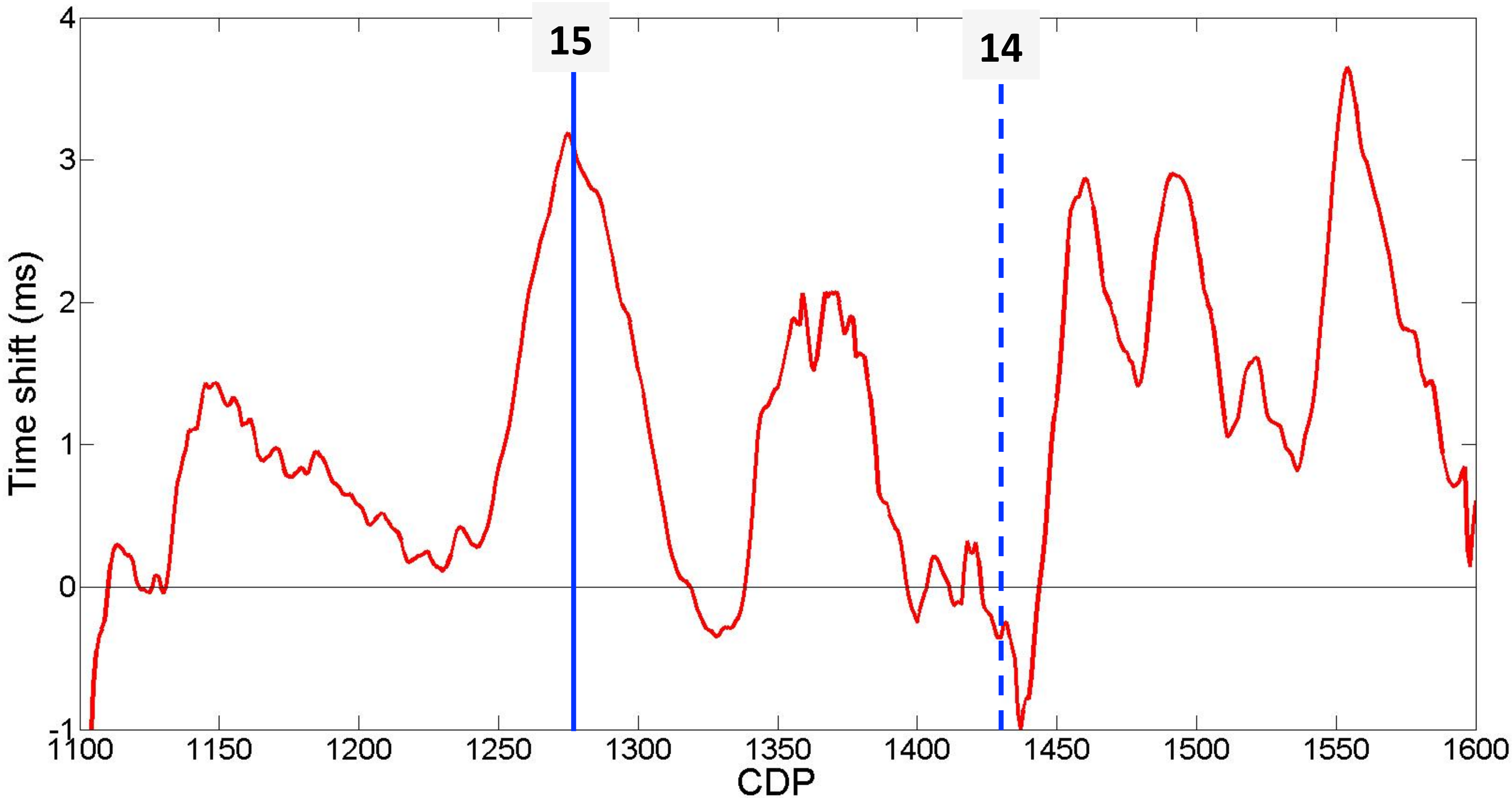


Smoothed timeshifts

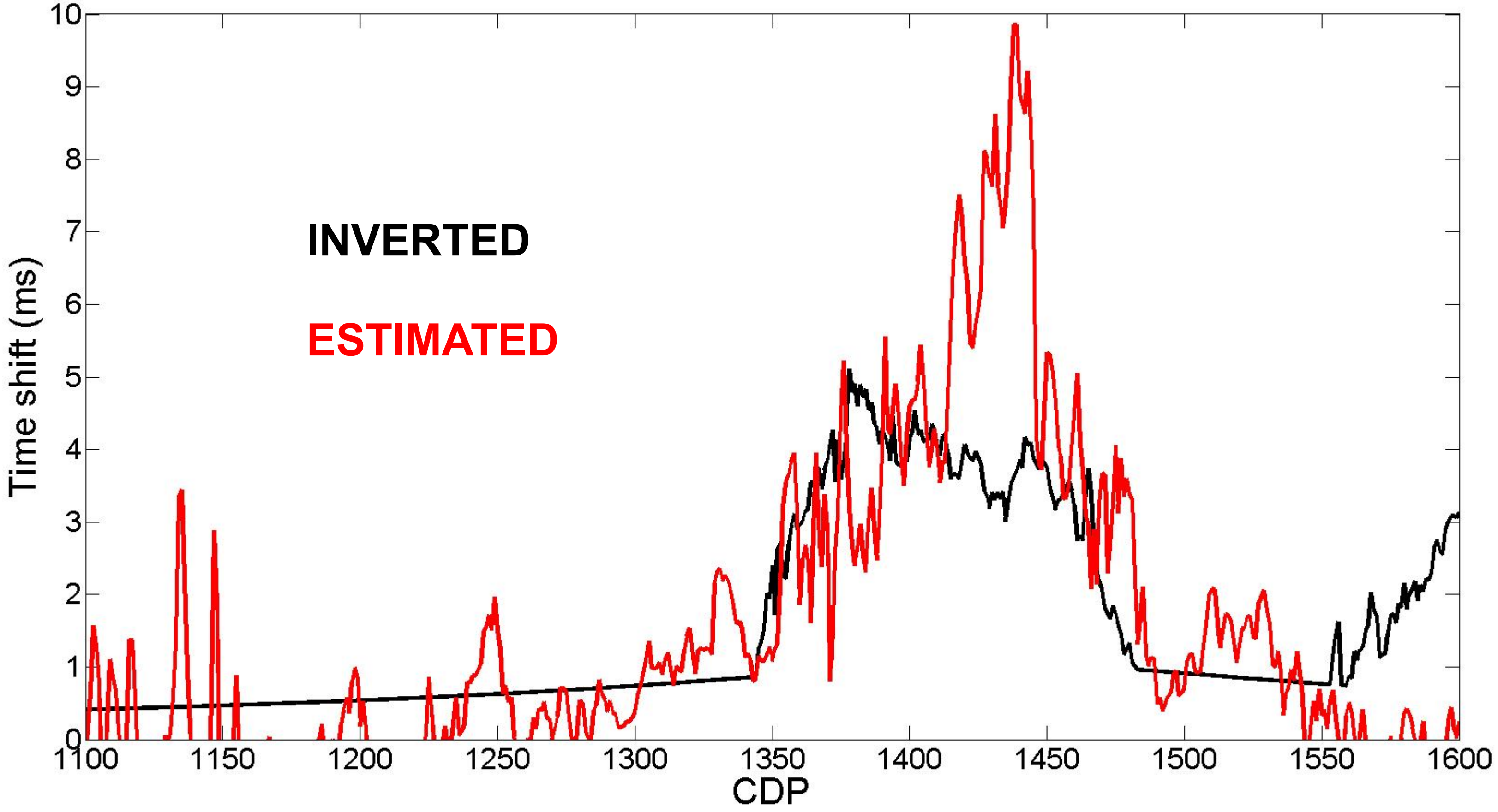


Note: Significant time shift increase close to relief well between 1990 and 2009

Time shift changes between 1990 and 2009



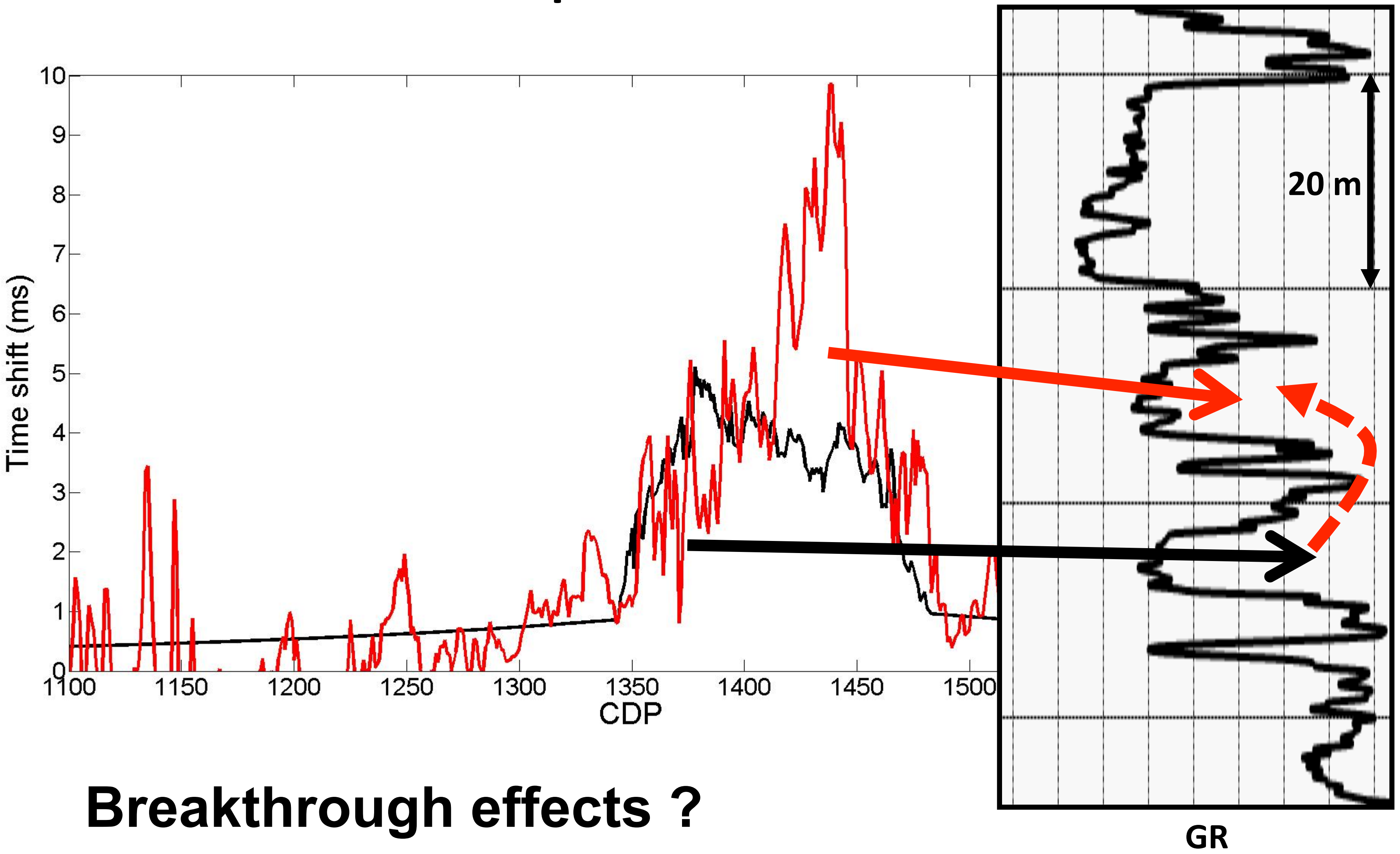
Inverted and estimated time shifts 1988-1990



Inversion result (L2-norm, full-loop inversion):

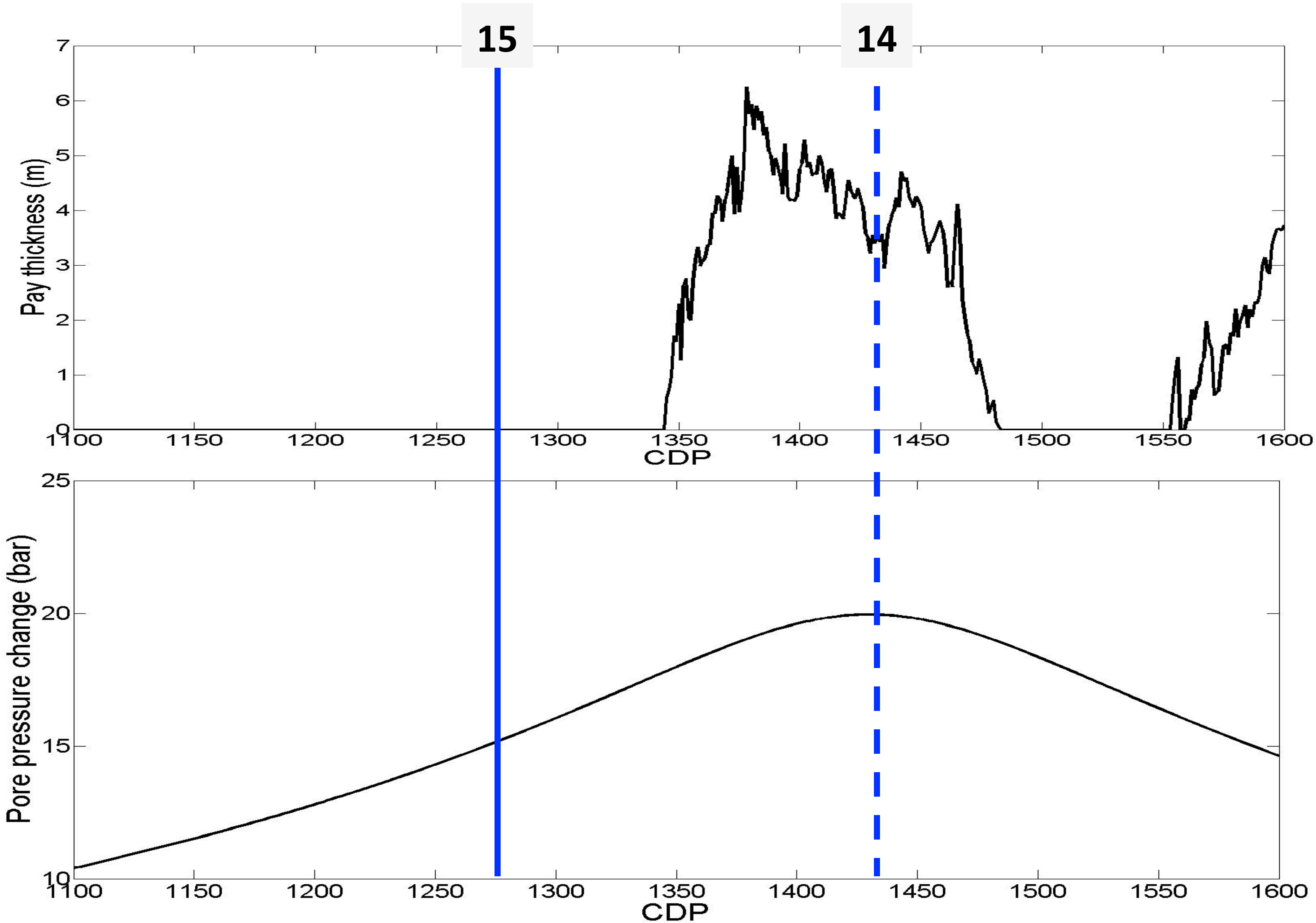
Pw = 80 bar; a = 7.5 bar and z0 = 442 m

Inversion does not explain all data:

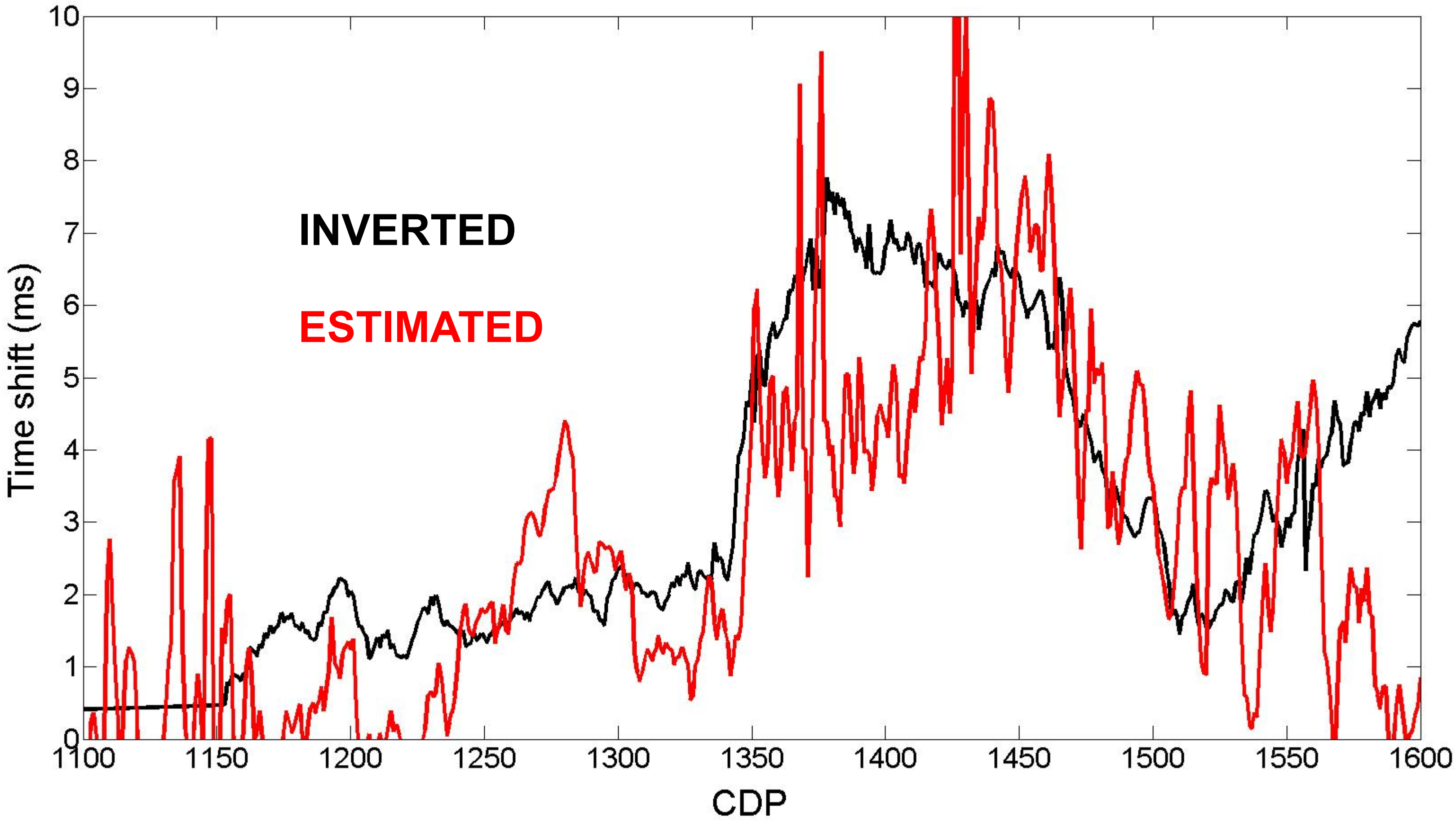


Breakthrough effects ?

Estimated pay thickness of gas and pressure changes 1988-1990

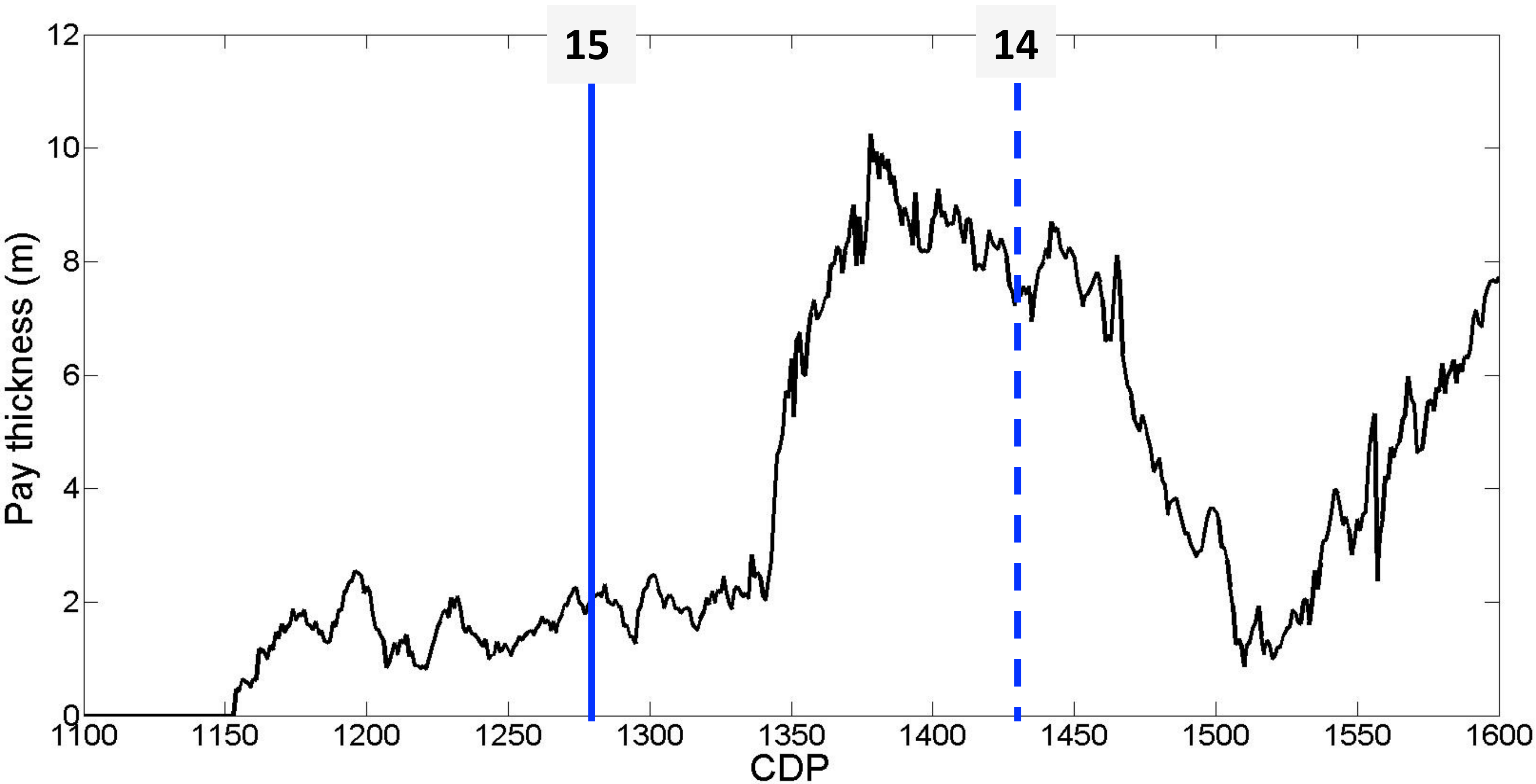


Inverted and estimated time shifts 1988-2009



NB: Keeping pressure constant from 1990 to 2009

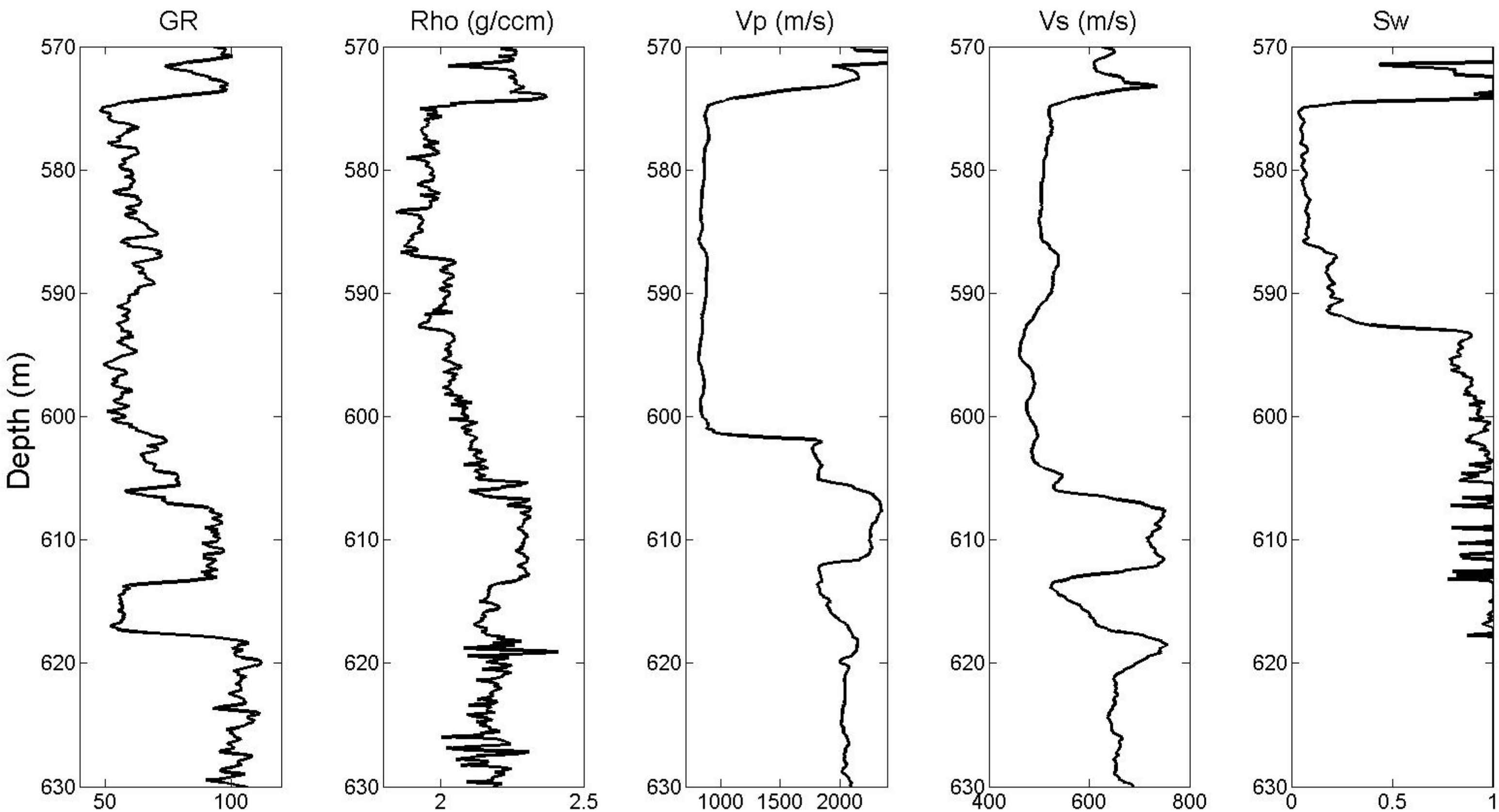
Pay thickness in 2009 assuming no pressure changes between 1990 and 2009

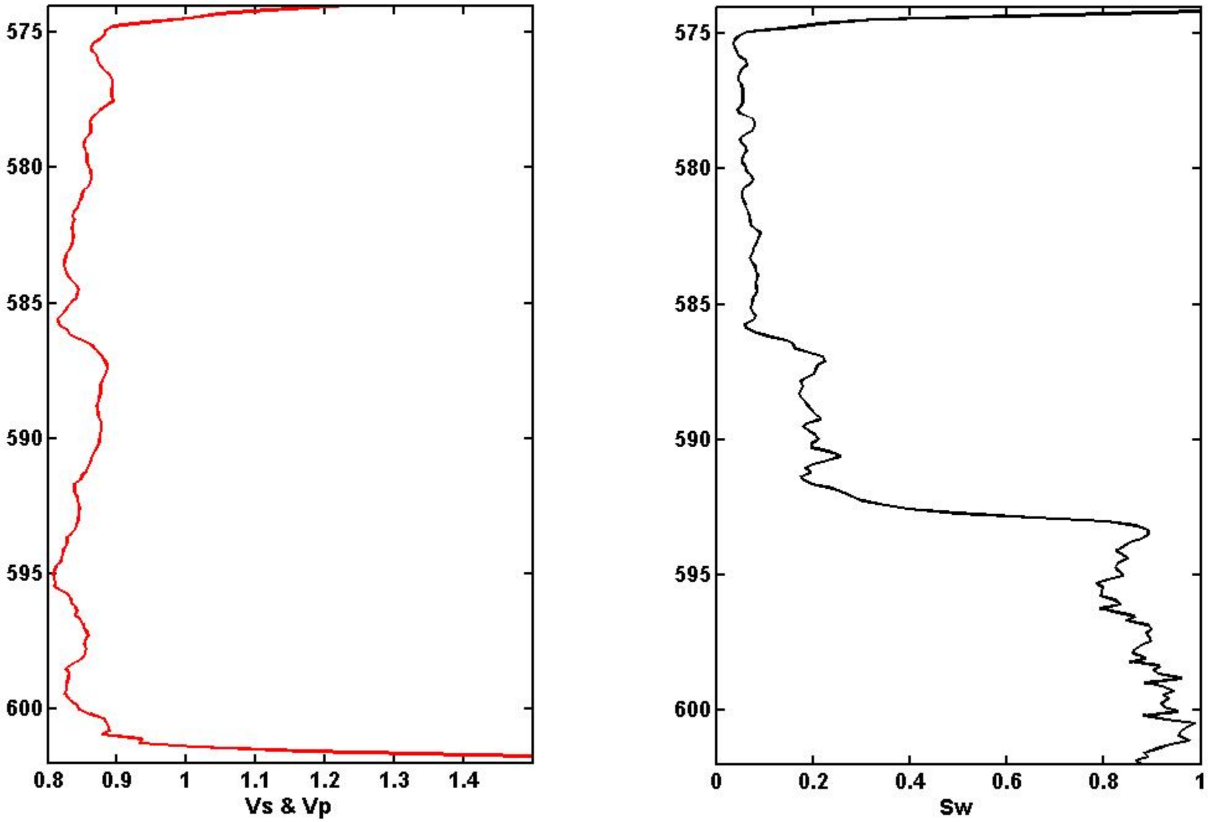


Summary

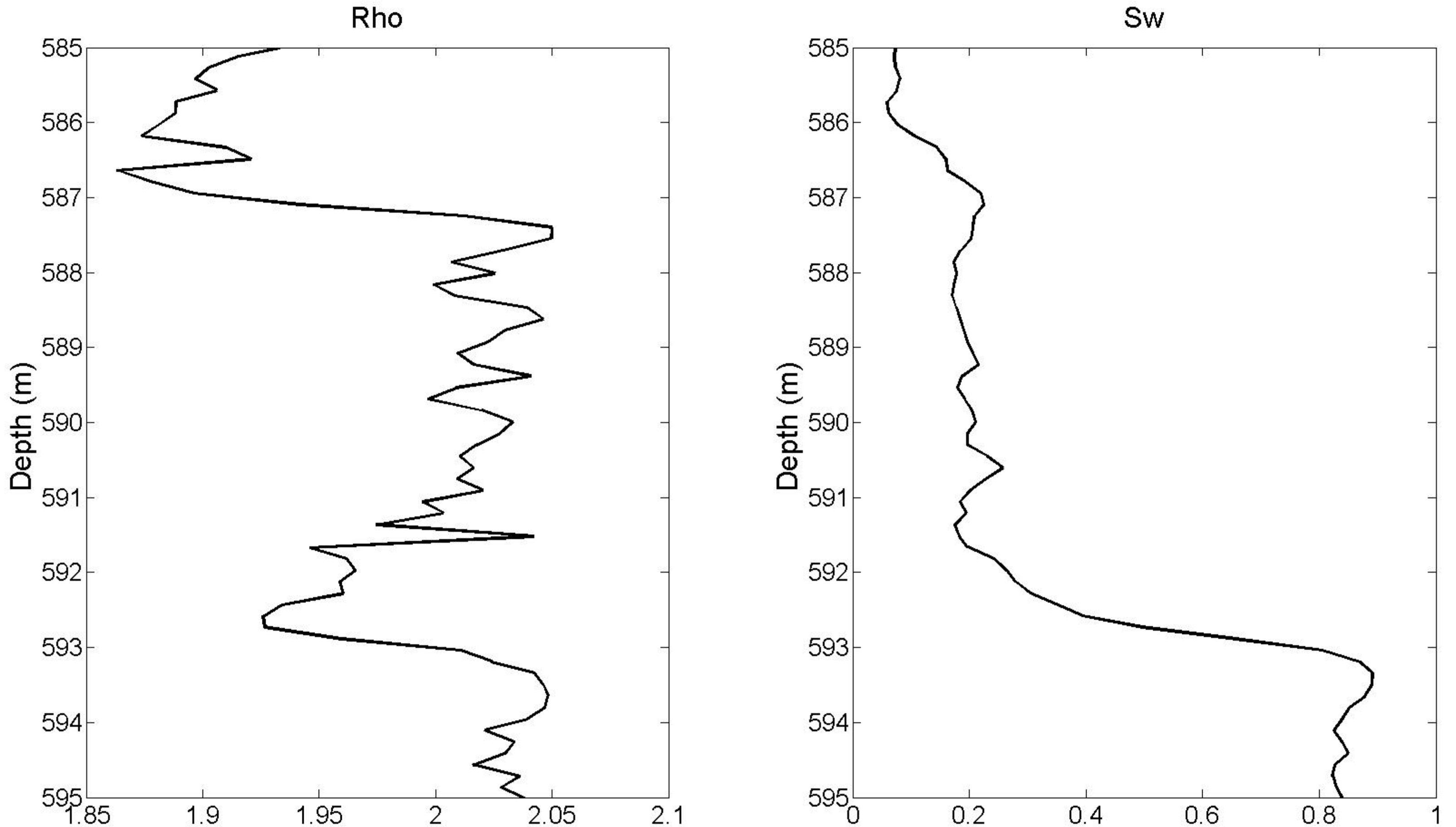
- Simple (too simple?) equation for determining the pressure variation in a shallow sand layer
- Time shifts modeled as a combination of saturation and pressure changes
- Inversion determines 3 parameters: thickness of gas, pressure at well position and decay rate of pressure away from well
- Inaccuracies in the structural interpretation of the top sand layer is a major source of uncertainties
- Need a more flexible way of defining the top reservoir geometry – more inversion parameters…

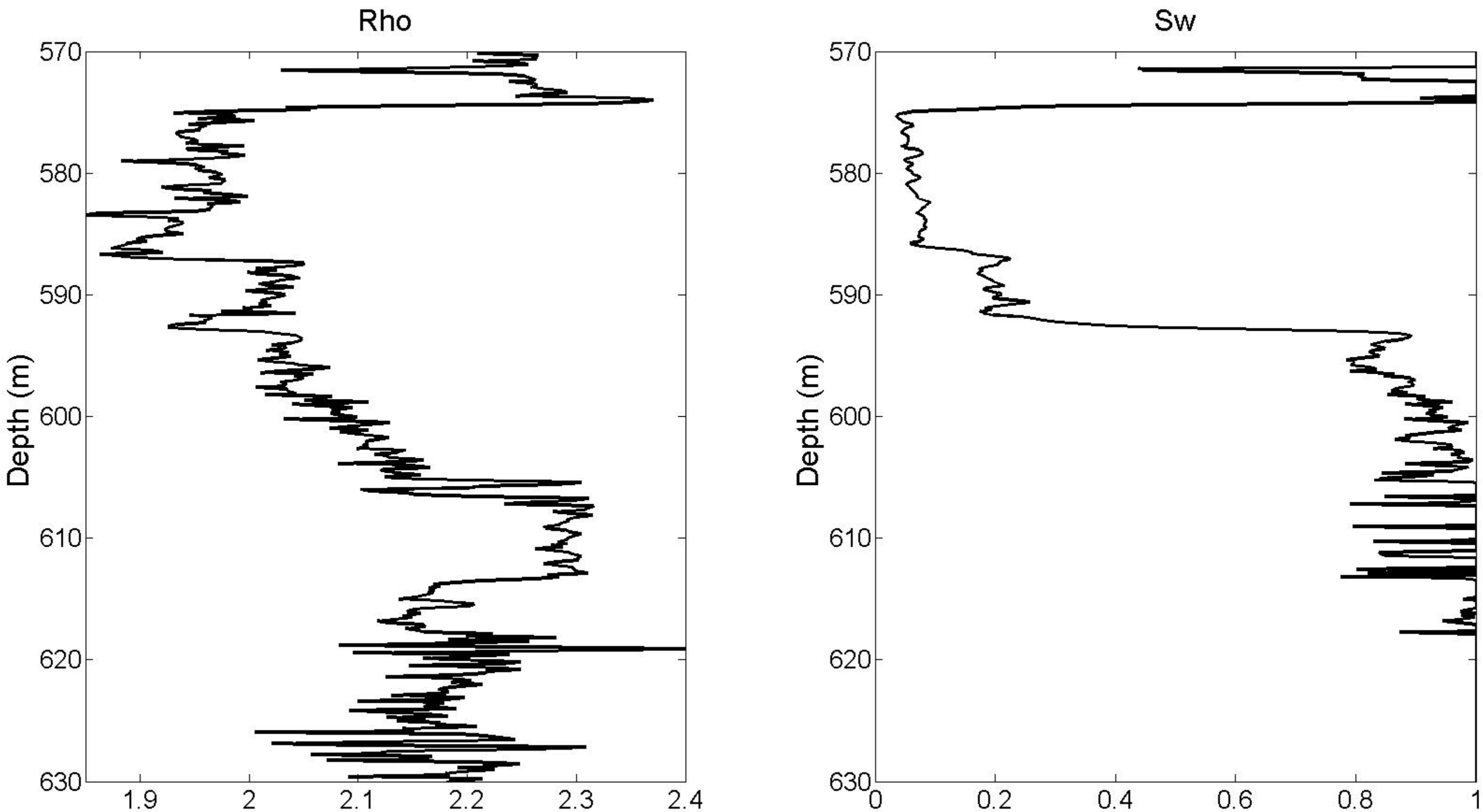
Peon field – logs




575
580
585
590
595
600
0.8 0.9 1 1.1 1.2 1.3 1.4
Vs & Vp
575
580
585
590
595
600
0 0.2 0.4 0.6 0.8 1
Sw

Detail showing that the saturation increase at 592 m correlates with a density increase of 0.12 g/ccm




Rho
Sw
Depth (m)
Depth (m)
570
580
590
600
610
620
630
1.9
2
2.1
2.2
2.3
2.4
0
0.2
0.4
0.6
0.8
1