Spatial reservoir characterization using the dilation factor α

Kenneth Duffaut
(Interpretation of Geophysical Data (IGD))

Faculty of Engineering Science and Technology
Department of Petroleum Engineering
and Applied Geophysics
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Norwegian University of Science and Technology

Outline

- Introduction
- Spatial traveltime analysis - a new application?
- Geological scenarios and numerical examples
- Conclusions

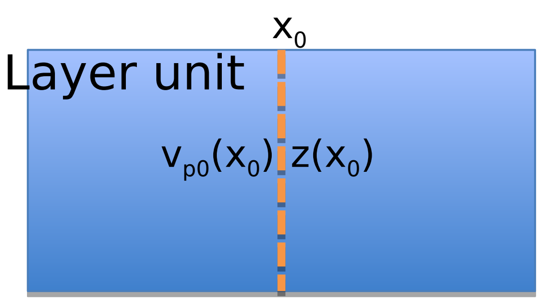
Introduction
4D or time-lapse traveltime analysis

$$t_0(x_0) = \frac{2z(x_0)}{v_{p0}(x_0)}$$

= two-way vertical time thickness of unit
= coordinate position along a line
= thickness of formation unit
$_{p0}$ = vertical P-wave velocity of unit
= changes in physical parameters
and R = ratio between relative velocity
nd thickness changes

$$\frac{\Delta t_0(x_0)}{t_0(x_0)} \approx \frac{\Delta z(x_0)}{z(x_0)} - \frac{\Delta v_{p0}(x_0)}{v_{p0}(x_0)}$$

(Landrø and Stammeijer 2004)



$$\frac{\Delta v_{p0}(x_0)}{v_{p0}(x_0)} = \alpha \frac{\Delta z(x_0)}{z(x_0)}$$

(Røste et al., 2005)

$$\frac{\Delta v_{p0}(x_0)}{v_{p0}(x_0)} = -R \frac{\Delta z(x_0)}{z(x_0)}$$

(Hatchell et al., 2005)

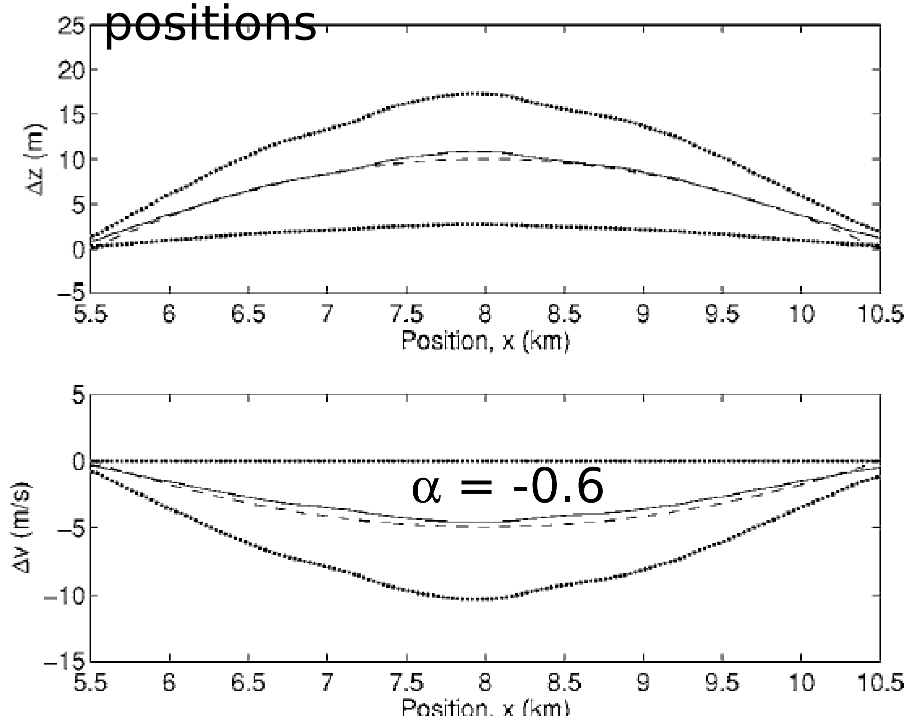
Assuming uniaxial deformation

Introduction
Relative changes in layer thickness and velocity

Optimal α = -0.6 for all lateral positions

$$\frac{\Delta z(x_0)}{z(x_0)} = \frac{1}{(1-\alpha)}\frac{\Delta t_0(x_0)}{t_0(x_0)}$$

$$\frac{\Delta v_{p0}(x_0)}{v_{p0}(x_0)} = \frac{\alpha}{(1-\alpha)}\frac{\Delta t_0(x_0)}{t_0(x_0)}$$



(Figure courtesy: Røste et al., 2006)

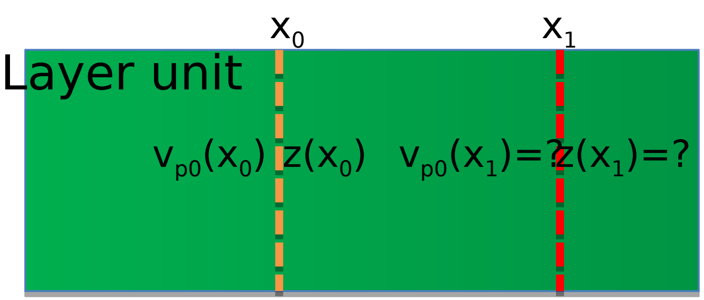
Spatial zero offset traveltime analysis

$$t_0(x_0) = \frac{2z(x_0)}{v_{p0}(x_0)}$$

= two-way vertical time thickness of unit at x_0
= coordinate reference position along a line
= a new coordinate position along the line
= thickness of formation unit
$_0$ = vertical P-wave velocity of unit
= spatial difference in physical parameters
= Dilation factor

$$\frac{\Delta t_0(x_1,x_0)}{t_0(x_0)} \approx \frac{\Delta z(x_1,x_0)}{z(x_0)} - \frac{\Delta v_{p0}(x_1,x_0)}{v_{p0}(x_0)}$$

$$\frac{\Delta v_{p0}(x_1,x_0)}{v_{p0}(x_0)} = \alpha(x_0)\frac{\Delta z(x_1,x_0)}{z(x_0)}$$



Assuming uniaxial deformation

Porosity-strain relation
Assume only changes in pore volume

Porosity $$\varphi = \frac{V_b - V_s}{V_b} = 1 - \frac{V_s}{V_b}$$ **Solid volume** **Bulk volume**

Rewritting we get

$$\frac{V_s}{V_b} = 1 - \varphi$$

Differentiation gives

$$\frac{d\varphi}{dV_b} = \frac{V_s}{V_b^2} \Rightarrow d\varphi = \frac{V_s}{V_b}\frac{dV_b}{V_b}$$ where $$\frac{dV_b}{V_b} = \epsilon_{vol}$$

We get porosity-strain relation

$$\frac{d\varphi}{(1-\varphi)} = \epsilon_{vol}$$

Spatial varying layer thickness and velocity

Relative changes in layer thickness and velocity

$$\frac{\Delta z(x_{1,}x_0)}{z(x_0)} = \frac{1}{(1-\alpha(x_0))}\frac{\Delta t_0(x_{1,}x_0)}{t_0(x_{1,}x_0)}$$

$$\frac{\Delta v_{p0}(x_{1,}x_0)}{v_{p0}(x_0)} = \frac{\alpha(x_0)}{(1-\alpha(x_0))}\frac{\Delta t_0(x_{1,}x_0)}{t_0(x_{1,}x_0)}$$

$$\frac{\Delta v_{p0}(x_1,x_0)}{v_{p0}(x_0)} = \alpha(x_0)\frac{\Delta\varphi(x_1,x_0)}{(1-\varphi(x_0))}$$

Dilation factor in clean and shaly sandstone Uniaxial deformation

Clean sandstone

$$v_{p0} = \mathrm{a} - \mathrm{b}\varphi$$

$$\frac{d\varphi}{(1-\varphi)} = \frac{dz}{z}$$

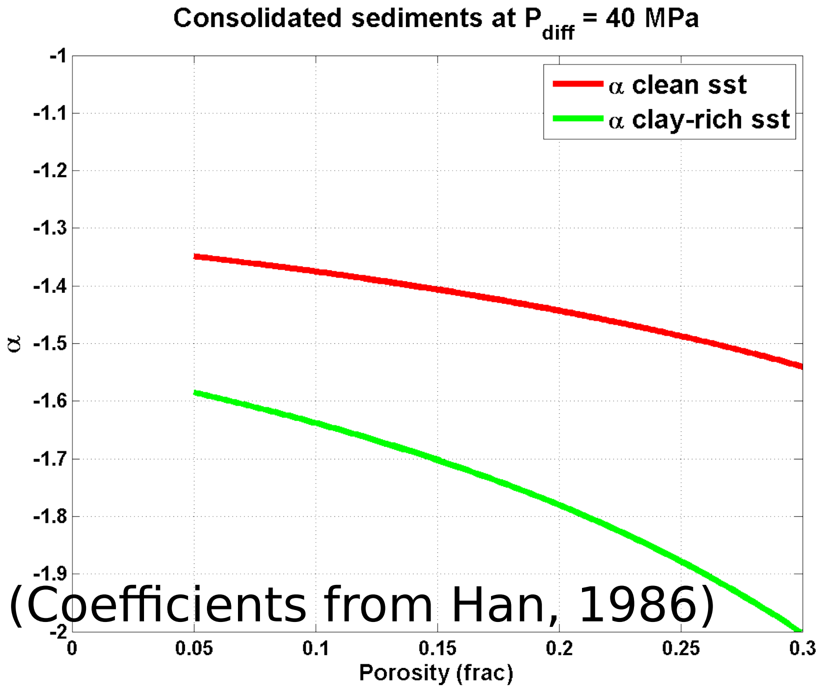
$$\frac{\Delta\varphi}{(1-\varphi)} = \frac{1}{\alpha}\frac{\Delta v_{p0}}{v_{p0}}$$

$$\alpha = \frac{(a-b)}{v_{po}} - 1$$ (Røste et al., 2006)

Clay-rich sandstone

$$v_{p0} = \mathrm{a} - \mathrm{b}\varphi - \mathrm{c}v_{cl}$$

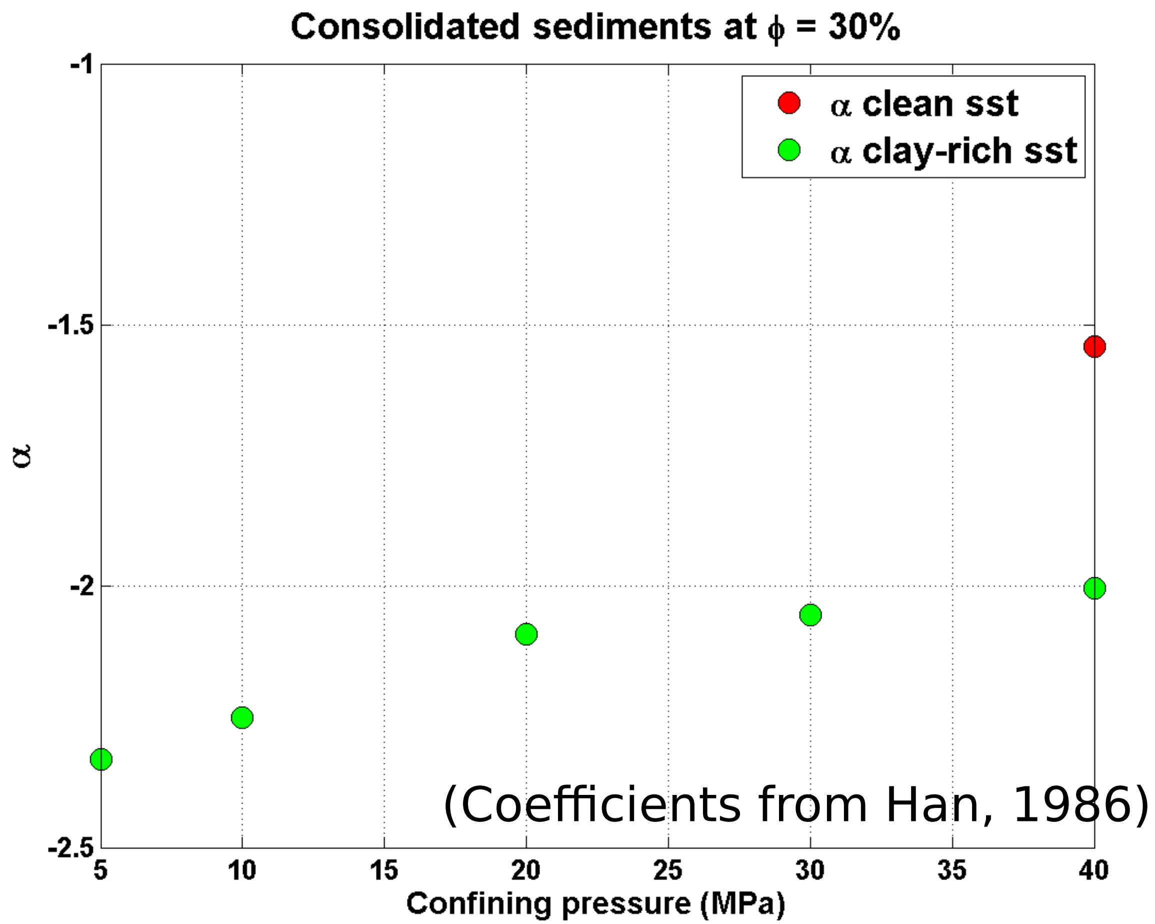
$$\alpha = \frac{(\varphi-1)b}{v_{po}}$$ (Carcione et al., 2007



(Coefficients from Han, 1986)

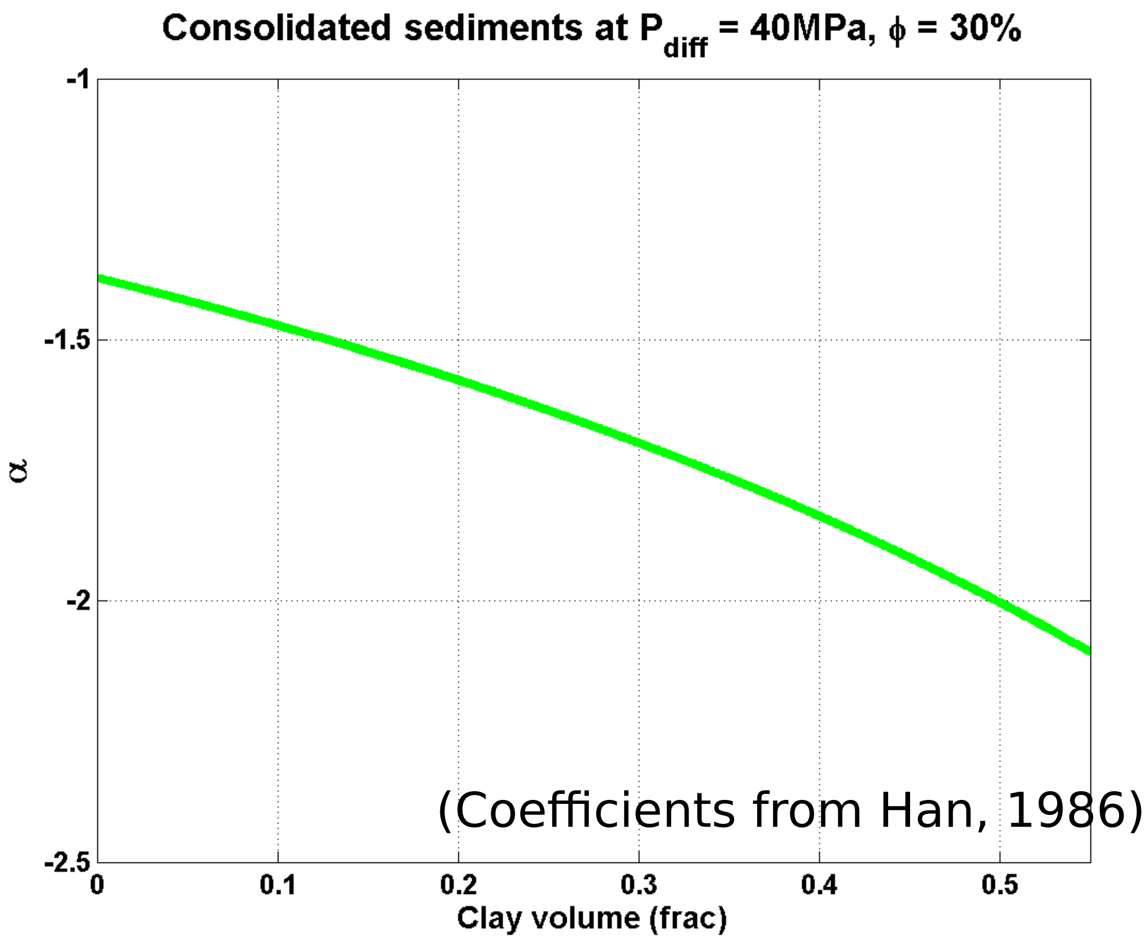
α decreases with decreasing porosity

Dilation factor vs. stress
Clean and clay-rich sandstone



α decreases with increasing net stress

Dilation factor vs. volume of clay



α decreases with decreasing clay content

Geological scenarios - numerical examples

- Plausible geological reasons causing spatially variation in layer thickness and velocity in a unit
  - Equal depositional layer thickness followed by ‘’differential compaction’’ or diagenetic effects within a formation unit
  - Erosion
  - Lithology changes
    - clean vs. shaly sandstone

Assume net stress = 40 MPa in all three cases

Spatial porosity and thickness change within unit
Differential compaction of clean sandstone

x_0 location with a well

φ = 24% **Z = 33m**

x_1 location without a well

φ = 20% **Z = 31m**

$$v_{p0}(x_0) = 6.08 - 8.06 * 0.24 \sim 4146 m/s$$

$$v_{p0}(x_1) = 6.08 - 8.06 * 0.20 = 4468 m/s$$

$$t_0(x_0) = \frac{2z(x_0)}{V_{p0}(x_0)}$$

$$t_0(x_0) = \frac{66m}{4146 m/s} \approx 0.01592s$$

$$t_o(x_1) = \frac{62m}{4468 m/s} \approx 0.01388s$$

$$\alpha_0 = \frac{(a-b)}{v_{p0}} - 1 = \frac{(6.08-8.06)}{4.146} - 1 \approx -1.48$$

Estimates of layer thickness and velocity at new location
Case: Differential compaction

Layer thickness estimate at x_1 location:

$$\frac{\Delta z(x_{1,} x_0)}{z(x_0)} = \frac{1}{2.48} \frac{(0.01388 - 0.01592)}{(0.01592)} \approx -0.0517$$

$$\tilde{z}(x_1) = z(x_0) + \Delta z(x_{1,} x_0) = 33\ m - 1.71 m \approx 31.3\text{m}$$

Correct $z(x_1) = 31\text{m}$

Velocity estimate at x_1 location:

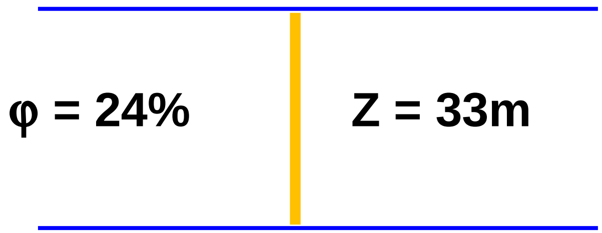
$$\frac{\Delta v_{p0}(x_{1,} x_0)}{v_{p0}(x_0)} = \frac{-1.48}{2.48} \frac{(0.01388 - 0.01592)}{(0.01592)} \approx 0.07647$$

$$\tilde{v}_{p0}(x_1) = v_{p0}(x_0) + \Delta v_{p0}(x_{1,} x_0) = 4146 + 317 = 4463\text{m/s}$$

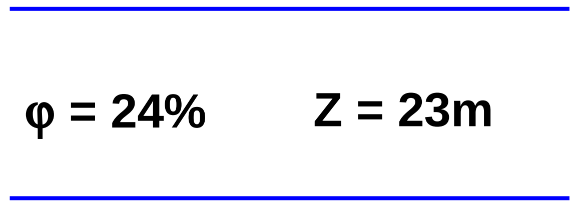
Correct $v_{p0}(x_1) = 4468\text{m/s}$

Spatially varying layer thickness
Erosion of a clean sandstone unit

x_0 location with a well



x_1 location without a well



$$v_{p0}(x_0) = 6.08 - 8.06 * 0.24 \sim 4146 m/s$$

$$v_{p0}(x_1) = 6.08 - 8.06 * 0.24 = 4146 m/s$$

$$t_0(x_0) = \frac{2z(x_0)}{V_{p0}(x_0)}$$

$$t_0(x_0) = \frac{66m}{4146m/s} \approx 0.01592s$$

$$t_o(x_1) = \frac{46m}{4146m/s} \approx 0.01110s$$

$$\alpha_0 = \frac{(a-b)}{v_{p0}} - 1 = \frac{(6.08-8.06)}{4.146} - 1 \approx -1.48$$

Estimates of layer thickness and velocity at new location
Case: Erosion

Layer thickness and porosity estimate at x_1 location:

$$\frac{\Delta z(x_1, x_0)}{z(x_0)} = \frac{1}{2.48}\frac{(0.01110 - 0.01592)}{(0.01592)} \approx -0.12221$$

$$\tilde{z}(x_1) = z(x_0) + \Delta z(x_1, x_0) = 33m - 4m = 29\text{m}$$

Correct $z(x_1) = 23\text{m}$

Correct

Velocity estimate at x_1 location:

$$\frac{\Delta v_{p0}(x_1, x_0)}{v_{p0}(x_0)} = \frac{-1.48}{2.48}\frac{(0.01110 - 0.01592)}{(0.01592)} \approx 0.1809$$

$$\tilde{v}_{p0}(x_1) = v_{p0}(x_0) + \Delta v_{p0}(x_1, x_0) = 4146\text{m/s} + 750\text{m/s} = 3396\text{m/s}$$

Correct $v_{p0}(x_1) = 4146\text{m/s}$

Correct

Spatial varying lithology clean vs. shaly sandstone unit

x_0 location with a well

φ = 24% **Z = 33m**

x_1 location without a well

φ = 12.5% **Z = 28m**

Vcl = 30%

$$v_{p0}(x_0) = 6.08 - 8.06 * 0.24 \sim 4146 m/s$$

$$v_{p0}(x_1) = 5.59 - 6.93 * 0.125 - 2.18 * 0.30 = 4070 m/s$$

$$t_0(x_0) = \frac{2z(x_0)}{V_{p0}(x_0)}$$

$$t_0(x_0) = \frac{66m}{4146m/s} \approx 0.01592s$$

$$t_o(x_1) = \frac{56m}{4070m/s} \approx 0.01376s$$

$$\alpha_0 = \frac{(a-b)}{v_{po}} - 1 = \frac{(6.08-8.06)}{4.146} - 1 \approx -1.48$$

Estimates of layer thickness and velocity at new location
Case: Lithological change

Layer thickness and porosity estimate at x_1 location:

$$\frac{\Delta z(x_1, x_0)}{z(x_0)} = \frac{1}{2.48} \frac{(0.01376 - 0.01592)}{(0.01592)} \approx -0.0547$$

$$\tilde{z}(x_1) = z(x_0) + \Delta z(x_1, x_0) = 33m - 1.8\text{m} \approx 31.2\text{m}$$

Correct $z(x_1) = 28\text{m}$

Correct

Velocity estimate at x_1 location:

$$\frac{\Delta v_{p0}(x_1, x_0)}{v_{p0}(x_0)} = \frac{-1.48}{2.48} \frac{(0.01376 - 0.01592)}{(0.01592)} \approx 0.081$$

$$\tilde{v}_{p0}(x_1) = v_{p0}(x_0) + \Delta v_{p0}(x_1, x_0) = 4146\text{m/s} + 336\text{m/s} \approx 4482\text{m/s}$$

Correct $v_{p0}(x_1) = 4069\text{m/s}$

Correct

Conclusions

- New approach tested by estimating relative changes in layer thickness and velocity using the dilation factor (α) and spatially traveltimes differences of a unit
  - A few numerical examples are shown.
    - Only the ''differential compaction'' case gave good estimates of laterally variable layer thickness (porosity) and velocity

- Method depends on
  - reference location
  - porosity-strain relation of the unit

- α is not constant when assuming Han's model. It decreases as
  - Porosity decreases (clean and shaly sandstones)
  - Clay content decreases
  - Net stress increases (shaly sandstone)

Acknowledge

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NTNU

Thank you for your attention