Amplitude variation with offset
AVO
and
Direct Hydrocarbon Indicators
DHI

Reflection at vertical incidence
Reflection coefficient $R(p)$ involves:
- Incident $P$-wave produces transmitted and reflected $P$-waves only.
- Why? Incident $P$-wave particle motion has component of motion in the directions of transmitted and reflected $S$-waves.

Reflection coefficient $R(p)$ is given by:

$$
\frac{(\alpha_2 \rho_2 - \alpha_1 \rho_1)}{(\alpha_2 \rho_2 + \alpha_1 \rho_1)}
$$

or

$$
\frac{\text{impedance difference}}{\text{impedance sum}}
$$

Reflection at oblique incidence
Reflection at non-vertical incidence involves mode conversion:
- Incident $P$-wave produces transmitted and reflected $S$-waves as determined by Snell's Law.

Reflection coefficients for all wave types' amplitudes are...

The Zoeppritz Equations
Energy partitioning coefficients for all wave types are...

Knott's Energy Equations
Reflection coefficient $R(p)$

Reflection at oblique incidence

P wavespeed $\alpha_1$
S wavespeed $\beta_1$
density $\rho_1$

P wavespeed $\alpha_2$
S wavespeed $\beta_2$
density $\rho_2$

The Zoeppritz Equations

Energy partitioning coefficients for all wave types’ amplitudes are ...

Knott’s Energy Equations

Reflection at oblique incidence

$\theta_{inc}$
$\theta_{trans}$

The “2-term Shuey’s Equation” is common: for $\theta \leq 30^\circ$,

$$R_p(\theta) = A + B\sin^2 \theta$$

where $A$ is the usual normal-incidence reflection coefficient, $B$ is a simple function of $\alpha_1, \beta_1, \rho_1, \alpha_2, \beta_2, \rho_2$ and $\theta$ is the incidence angle.
Increasing source-receiver offset... is equivalent to increasing angle of incidence.

Hence, in a CMP gather, along an individual reflector, the amplitudes at each offset (after correction for geometric spreading and anelastic attenuation) can be measured. A velocity model is used to convert offsets to angles of incidence. Linear regression on a plot of recorded amplitude vs. \( \sin^2(\theta) \) be used to find \( A \) and \( B \). NB! Needs careful processing to ensure true relative amplitudes are preserved.

Example:

Along the \(-640\)ms event there is a locally stronger trough and peak, as indicated by the red arrow.

Example:

View the pre-stack data?
Example

Figure 6. The intercept and gradient B is the top and base reflections from a gas sand.

Trough is top reservoir (shale over gas sand), peak is base reservoir.

(a) Small window from gather

Why all the interest?

Maps or crossplots of AVO responses can be used to detect pore-fill anomalies, i.e., hydrocarbons and map their lateral extent.

How wide is the reservoir? Can AVO answer this?

Time Lapse
Fluid Saturation & Porosity

Key factor in time lapse 4D reservoir monitoring and angle dependent reflectivity (AVO) is the seismic response due to fluid saturation and fluid substitution.

Rocks saturated with less compressible fluids, e.g. oil, brine etc, show higher Vp and impedances.

Vs impedances are much less affected by pore fluids because fluids have no rigidity.

Therefore rocks with less compressible fluids have higher Vp/Vs ratios.

This is the basis for use of angle-dependent reflectivity for direct hydrocarbon detection and fluid substitution.

However, seismic reflectivity proportional to both fluid and matrix (rock) properties.

E.g. low porosity rock with flat, low aspect ratio pores may have a lower velocity than a high porosity rock with spherical pores since flat pores are more compressible than spherical pores.

I.e. Rocks with cracks of fractures always show a large effects of fluid substitution since cracks are very compliant.

4D seismics

Seismic characteristics change spatially with time as reservoir is produced:

Causes changes in the physical properties = changes in seismic reflection characteristics:

Seismic Amplitude - acoustic impedance variations

Seismic Amplitude with Offset - AVO, Vp/Vs
4D seismics

4D = 3D surveys repeated with time

4C = 4 components – 3 geophone + pressure

Uses of 4D

• Identification of infill targets
• Location of boreholes
• Check on how reservoir is producing
• Health and Safety issues (pressure conditions)
• Gas disposal assurance

3D surveys since ~1989
4D surveys since ~1999

1999 Data
Pre-Production

Amplitude increase suggests pressure drop across a more well length

2000 Data
Post-Production
The Life of Field Seismic Array

- Highest concentration of seismic sensors in the world.
- 10,000 sensors
- 2,500 locations on the sea bed
- 120 km of cabling
- Each station has 3C of motion + hydrophone recording.

Recording during hydraulic fracturing

- Vertical component
- 15-30 Hz band pass
- Envelope function

Direct Hydrocarbon Indicators
1 Introduction

Velocity and density of sedimentary rocks (particularly clastic rocks) depend primarily on porosity and the properties of the pore fluid. Gas within the pore space of a clastic rock lowers $V_p$ substantially but leaves $V_s$ relatively unaffected. Thus gas entering the pore spaces of a reservoir affects the reflection coefficients at the top and bottom of the reservoir. These effects can be used as direct hydrocarbon indicators (DHI’s). Confidence in the accuracy of DHI identification can be increased by modelling.

2 Summary of Hydrocarbon Indicators

(After Brown 1991 Interpretation of 3D Seismic Data AAPG Memoir 42)

i) Structural crest of against a fault: Trapping location
ii) Local increase in amplitude: Bright Spot
iii) Local decrease in amplitude: Dim Spot
iv) Discordant flat reflector: Flat Spot
v) Local waveshape change: Polarity reversal
vi) Reservoir limits consistent: Consistent model
vii) Polarities consistent: -ve over rock/gas
viii) Low frequencies underneath: Attenuation shadow
ix) Time sag underneath: Velocity sag
x) Lower amplitudes underneath: Amplitude shadow
xi) Increase in amplitude with offset: AVO anomaly
xii) P-wave but no S-wave anomaly: S-wave support
xiii) Data deterioration: Gas chimney
Summary of Hydrocarbon Indicators

[After Brown 1991 Interpretation of 3D Seismic Data AAPG Memoir 42]

i) Structural crest of against a fault - Trapping location
ii) Local increase in amplitude - Bright Spot
iii) Local decrease in amplitude - Dim Spot
iv) Discordant flat reflector - Flat Spot
v) Local waveshape change - Polarity reversal
vi) Reservoir limits consistent - Consistent model
vii) Polarity consistent - +ve over rock/gas
viii) Low frequencies underneath - Attenuation shadow
ix) Time sag underneath - Velocity sag
x) Lower amplitudes underneath - Amplitude shadow
xi) Increase in amplitude with offset - AVO anomaly
xii) P-wave but no S-wave anomaly - S-wave support
xiii) Data deterioration - Gas chimney

Bright Spots

- In the 1960's geophysicist recognized the usefulness of displaying seismic reflection sections as 'true amplitude' rather than overuse AGC in the identification of amplitude anomalies.
- 'Bright spots' - amplitude highs - were associated with hydrocarbon accumulations; due to the increase in reflection coefficient at top and bottom of a reservoir caused by gas in the pore space.

- Effect generally greater and simpler for relatively unconsolidated clastic rocks (e.g. Tertiary clastic basins - very successful in the Gulf of Mexico).
- Relationship between hydrocarbon indicators and hydrocarbon accumulations is not simple and universal - bright spots result from changes other than commercial hydrocarbon accumulations - low saturation of gas (see plot of gas saturation v. reflection coefficient), igneous intrusions, carbonates, coals.
**Dim Spots**

If the rock overlying the reservoir has a velocity appreciably lower than that of the reservoir itself (e.g. carbonate reservoir capped by shales), the effect of hydrocarbon is to decrease the contrast in acoustic impedance and reduce the reflection coefficient producing a 'dim spot'.
Polarity Reversals
Where the rock overlying the reservoir has a velocity slightly smaller than that of the reservoir rock, lowering the reservoir rock by hydrocarbons may invert the sign of the reflection, producing a polarity reversal.

Flat Spot
Where a well-defined fluid contact is present (esp. gas/oil or gas/water) the contrast may be large enough to give a fairly strong flat reflection that may stand out on the seismic records.
‘Shadow’ Effects

The lowering of the velocity in a hydrocarbon accumulation will affect the travel times from deeper reflections by increasing travel-times to cause a reflection sag (usually small).

The high amplitudes of a bright spot are often processed in such a way as to cause a lower amplitude shadow zone above a bright spot as well as below.

Lowering of instantaneous frequency

is often observed immediately under hydrocarbon accumulations (for a few cycles). Such low frequency shadows may be due to absorption or ray path distortion by the reservoir producing stacking velocity errors.
Gas chimney

- A subsurface leakage of gas from a poorly sealed hydrocarbon accumulation.
- The gas can cause overlying rocks to have a low velocity. Gas chimneys are visible in seismic data as areas of poor data quality or push downs.