C2.9 Hydrocarbon exploration with seismic reflection

Seismic processing includes the steps discussed in class:

(1) Filtering of raw data

(2) Selecting traces for CMP gathers

(3) Static corrections

(4) Velocity analysis

(5) NMO/DMO corrections

(6) CMP stacking.

(7) Deconvolution and filtering of stacked zero offset traces

(8) Migration (depth or time)

Question : This sequence is for **post-stack** depth migration. How will it change for **pre-stack** depth migration?

Processed seismic data can contribute to hydrocarbon exploration in several ways:

- Seismic data can give **direct evidenc**e of the presence of hydrocarbons (*e.g.* bright spots, oil-water contact, amplitude-versus-offset anomalies).

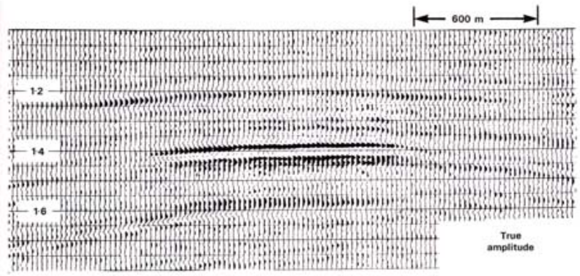
- Potential **hydrocarbon traps** can be imaged (*e.g.* reefs, unconformities, structural traps, stratiagraphic traps etc)

- Regional structure can be understood in terms of depositional history and the timing of regression and transgression (seismic stratigraphy, seismic facies analysis). This can sometimes give an understanding of where potential source rocks are located and the relative age of reservoir rocks.

C2.9.1 Direct indicators of hydrocarbons

2.9.1.1 Bright spots

As shown in C1.3, a gas reservoir can have a P-wave velocity that is significantly lower that the surrounding rocks. This can lead to a high amplitude (negative polarity) reflection from the top of the reservoir.



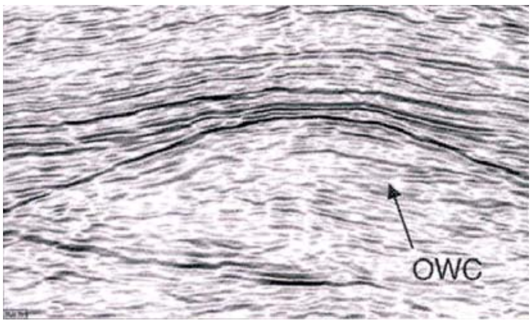
- However, not all bright spots are hydrocarbons. They can be caused by sills of igneous rocks or other lithological contrasts. In areas of active tectonics, ponded partial melt can produce a bright spot (*e.g.* Southern Tibet).

- It should also be noted that **true amplitudes** are not always preserved in seismic data recording and processing. When data is recorded, the amplification of the signal varies from trace to trace. It can also vary with time in a given trace (later signals have travelled deeper and have a smaller amplitude so the amplification is increased). Thus variations from trace to trace in a seismic section do not necessarily imply a change in a sub-surface property.

- **Focussing and defocusing** effects on an undulating interface can also change the measured amplitude. Beware!

2.9.1.2 Hydrocarbon-water interface

Example 1 : Fulmar field, North Sea

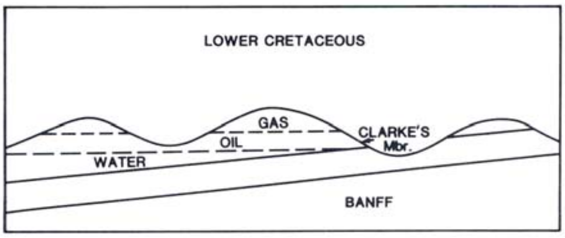


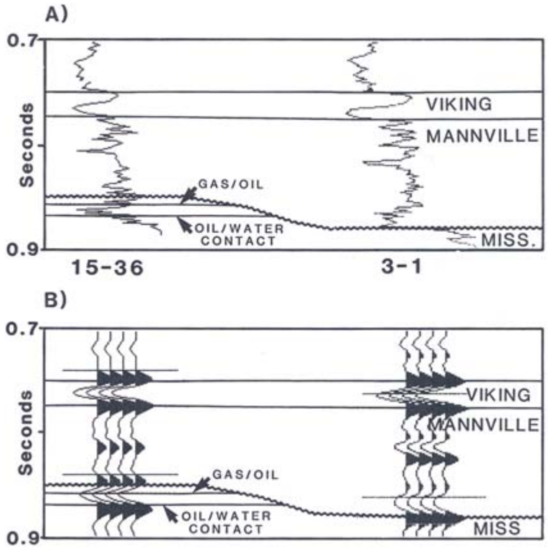
The oil-water contact is flat in this depth section from the Fulmar field in the North Sea (Kearey 4-39). Note that it crosses reflectors in the anticline.

Example 2 : The Alba Field, North Sea

Details in *Macleod et al*., (1999)

Example 3 : Alexis Field, Alberta





- The Alexis Field, 65 km NW of Edmonton, Alberta is described in Chapter 6 of *Andersen et al*, 1989. The oil and gas reservoir is located in a structural remnant of dolomitized carbonate of the Mississippian age Banff formation. Upper surface is erosional in nature and overlying rocks are lower velocity Cretaceous shales and sandstones.

- The seismic data use the reflection from the Viking Fm as a **datum**. This requires all the seismic traces to be aligned on this reflector. This removes any residual statics and the velocity effects of shallower structure. This is necessary because variations in the reflection from the reservoir are quite subtle.

- To interpret the seismic reflections, velocity measurements are made in wells (sonic logs). From the variation of velocity with depth, a **synthetic seismogram** can be computed. This is the predicted seismic trace that would be measured at this location. It allows us to determine which velocity and lithology changes will be detectable in surface seismic data.

- Remember that the finite wavelengths of seismic data do not allow features less than $\lambda/4$ in thickness to be imaged (section C2.6).

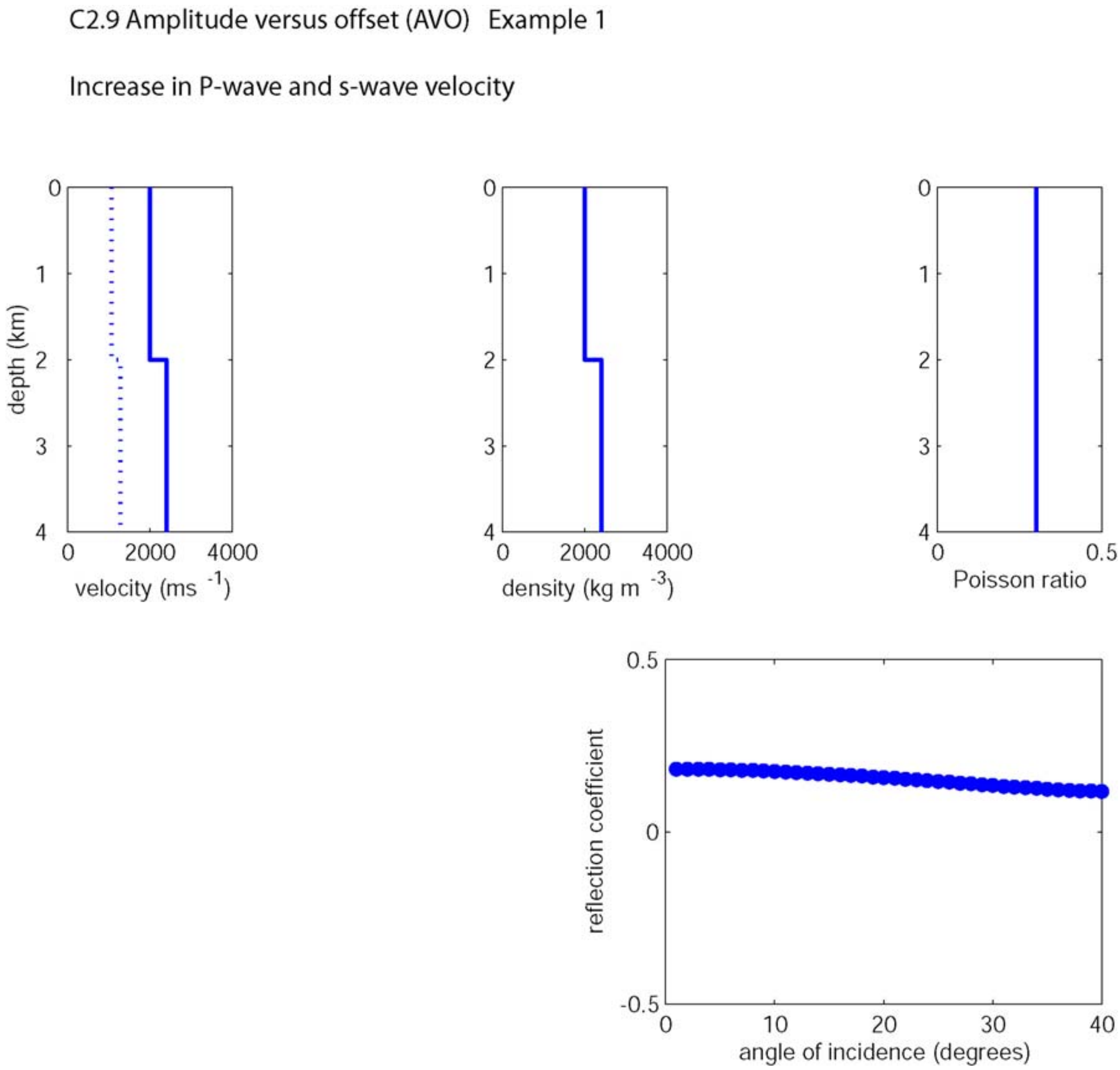
- The reservoir in this case is quite thin, and completely separate reflectors are not seen from the upper and lower interfaces. However, the shape of the reflector changes distinctly between a wells in the reservoir (15-36) and a well outside the reservoir (3-1).

2.9.1.3 Amplitude versus offset (AVO)

Previously we computed reflection coefficients for seismic waves incident at normal incidence. However, the full Zoeppritz equations predict that the reflection coefficient will **vary with the angle of incidence**. The two examples below were generated with MATLAB script **AVO_simple.m** and illustrate this phenomena.

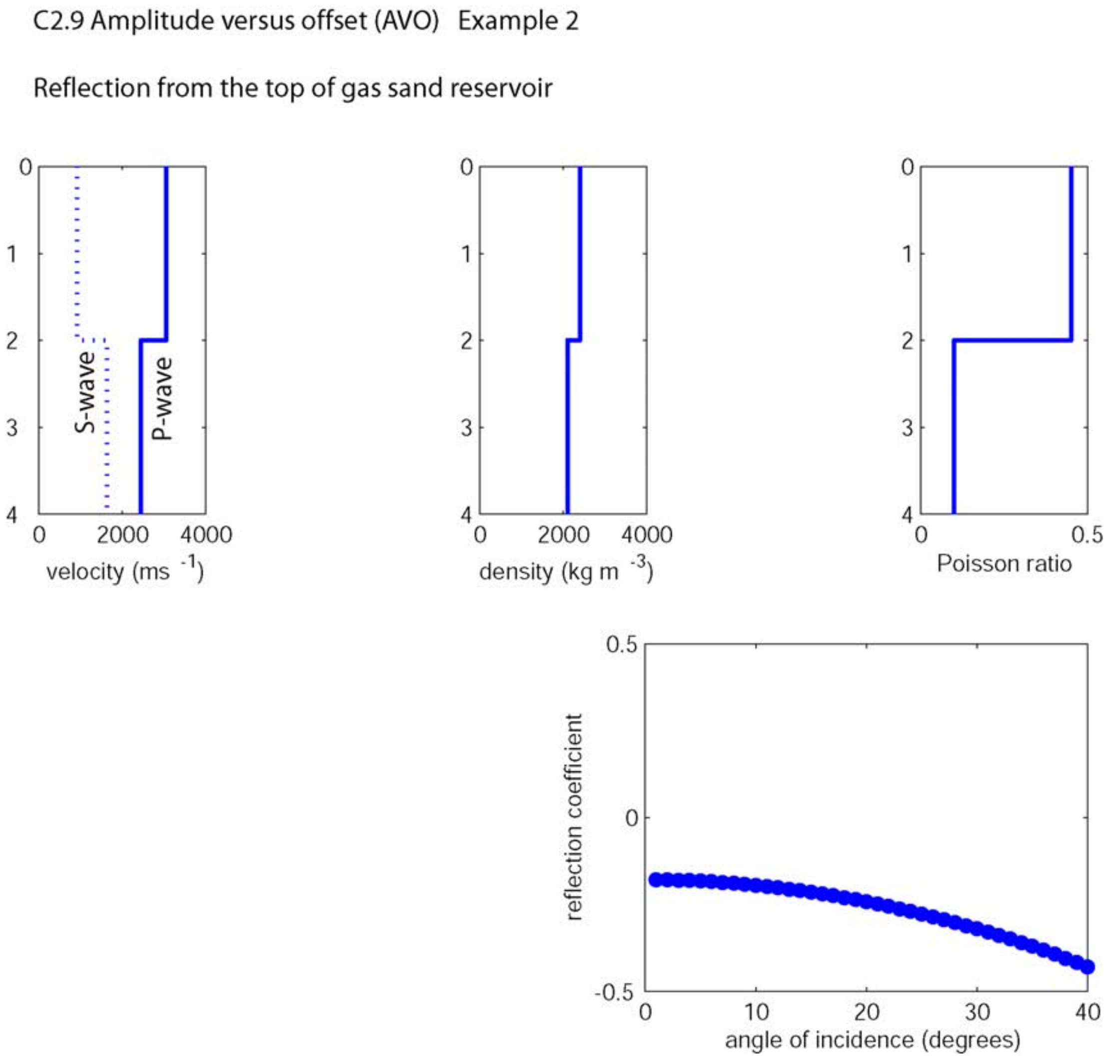
Example 1

Both P-wave and S-wave velocities **increase** across the interface. Remember that at non-normal incidence, an incident P-wave will generate 4 new waves. These are the reflected and transmitted P-waves **and** the reflected and transmitted S-waves. The reflection coefficient of the P-wave decreases with angle in this example.



Example 2

This example simulates the effect of shale overlying a gas saturated sand reservoir. The P-wave velocity **decreases**, giving a **negative reflection coefficient** at normal incidence.



The S-wave velocity **increases** from the shale into the gas sand. Why?

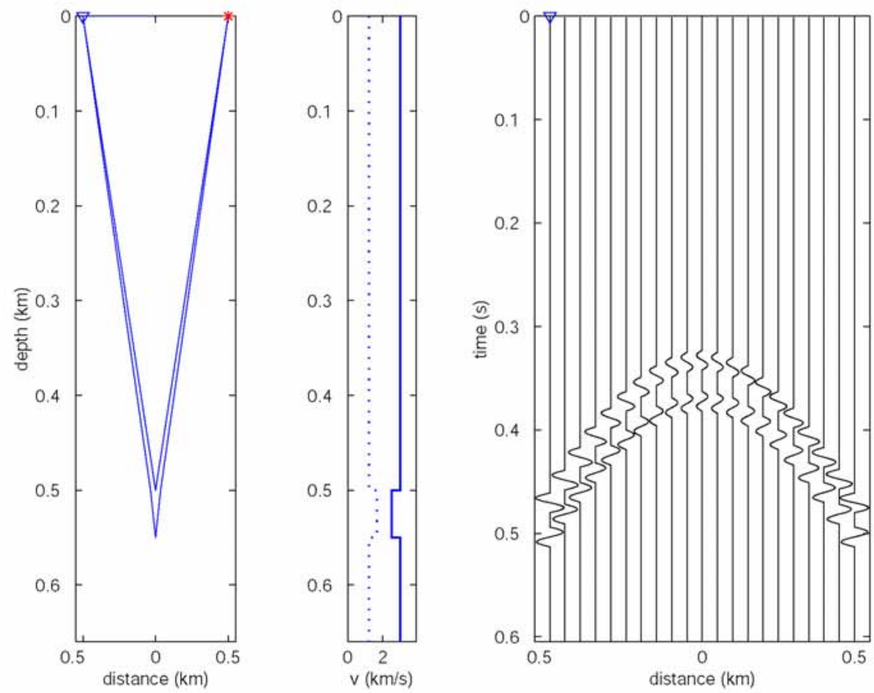
Can show that this corresponds to a **decrease** of Poisson's ratio

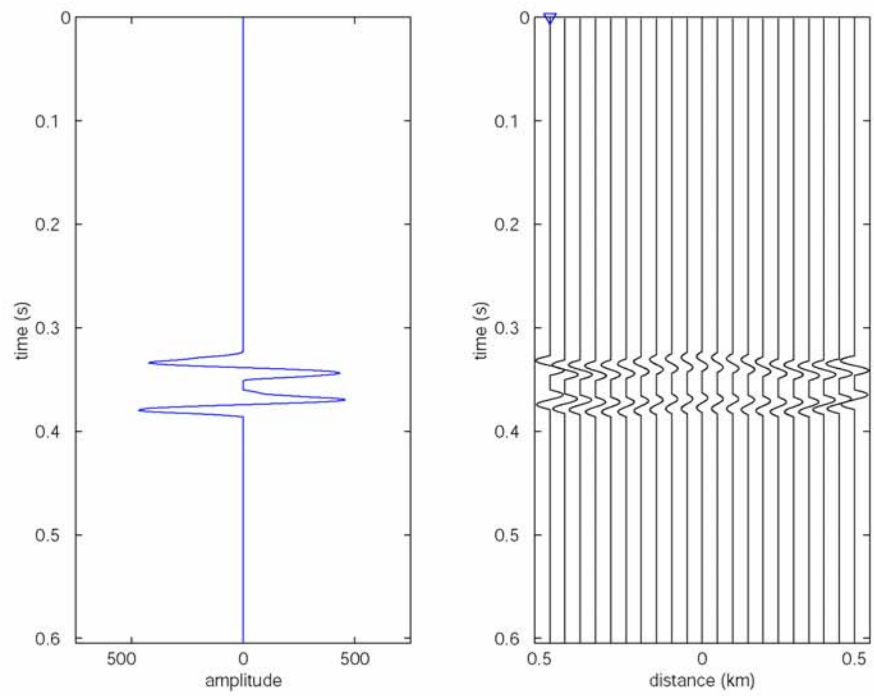
$$\sigma = \frac{(v_P / v_S)^2 - 2}{2((v_P / v_S)^2 - 1)}$$

Poisson's ratio is usually around 0.5 for incompressible materials, and softer material will have values in the range 0 to 0.2 In this case, the P-wave reflection coefficient becomes larger as the angle of incidence increases. Since an **increase in angle** corresponds to a **greater source-receiver offset**, this is called an amplitude-versus offset (AVO) anomaly.

The effect of AVO effects on a synthetic CMP gather are shown with **cmp_v4.m**

C2.9 AVO effects in a CMP gather

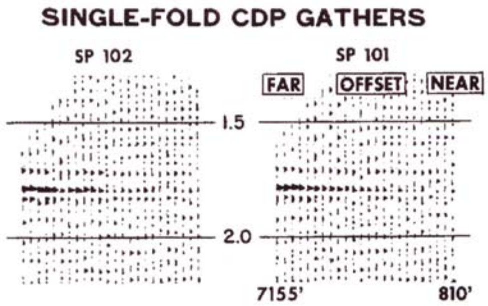




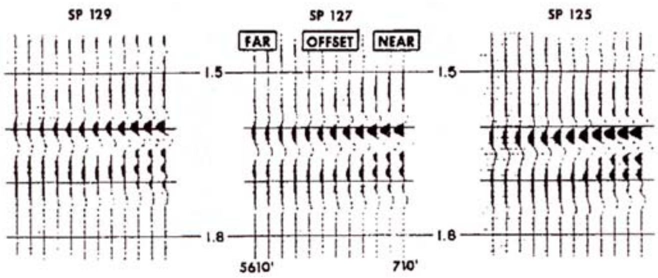
Stack at 3350 m/s

Data examples of AVO

These effects are often present in field data and can indicate the presence of oil or gas with more reliability than normal incidence reflection data. The following example is taken from *Ostrander* (1984) and shows a reflection from a known gas reservoir at a depth of 6700 feet in the Sacramento Valley, California. The amplitude **increases** with offset on a number of CDP gathers.



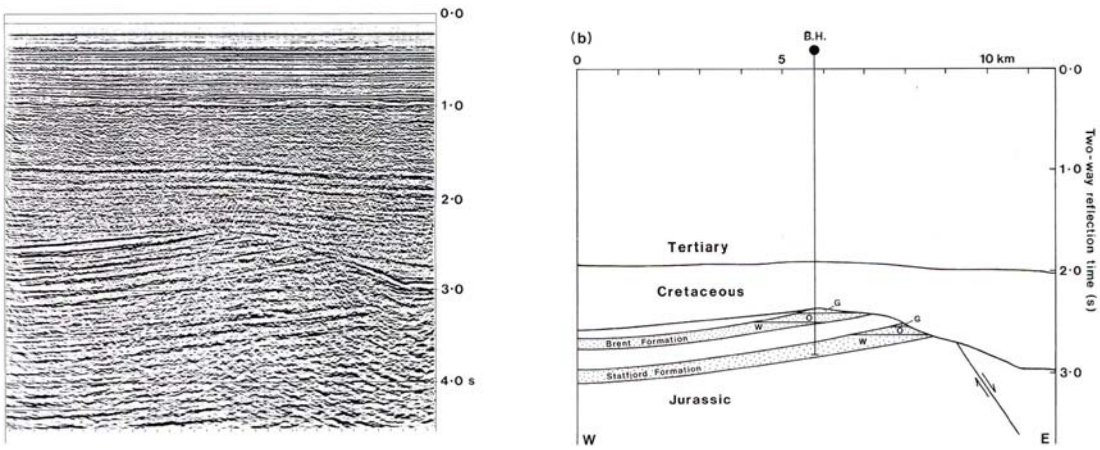
In this example, also from *Ostrander* (1984), a high amplitude reflection in a sedimentary basin in Nevada was analysed. The amplitude **decreases** with offset, suggesting that the layer had a normal Poisson's ratio. It was subsequently drilled and shown to be 160 feet of basalt.



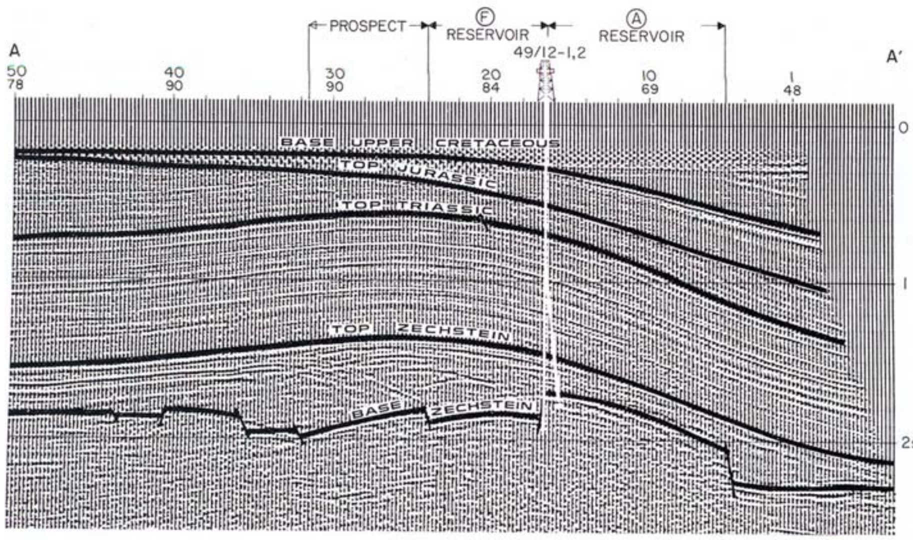
C2.9.2 Images of hydrocarbon reservoirs on seismic sections

To illustrate some of the concepts used in interpretation, we will look at a number of seismic sections from a range of tectonic settings. In Labs 6 and 7 you will work though a couple of examples on your own (and realize what it takes to draw lines on a blank section!).

2.9.2.1 Extensional environment – North Sea



Brent oilfield, North Sea, *Kearey Figure 4.62*



Viking gas field, North Sea, *Kearey 4.61*. Gas reservoir is located in a faulted anticline. The most prominent reflections in a seismic section are called markers. These are correlated across the section though a comparison of their character and sequence. They are tied to lithologic units through measuring well logs and computing synthetic seismograms. Vertical seismic profiles can also be used in this respect.

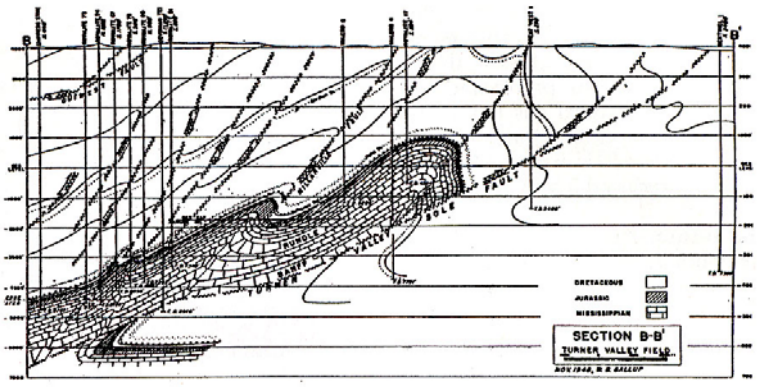
2.9.2.2 Fold and Thrust belts

Wyoming, South Elk Basin

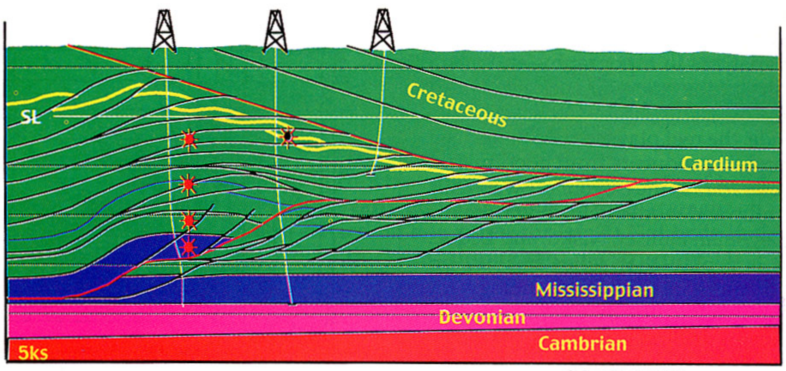
Interpretation Lab 6 : Tracing reflectors across a series of faults can be more difficult in this environment, but is quite possible, as will be demonstrated in Lab 6

Rocky Mountain Foothills

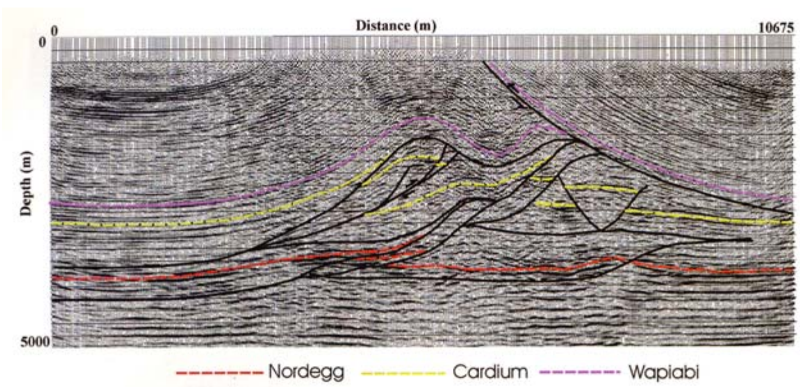
Turner Valley *Anderson et al*, 1989, page 165



(After Gallup, 1951)

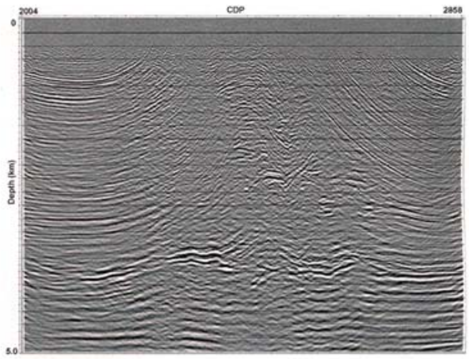


(After Teal, 1983)



Yan and Lines, The Leading Edge, (2001)

Post–stack depth migration



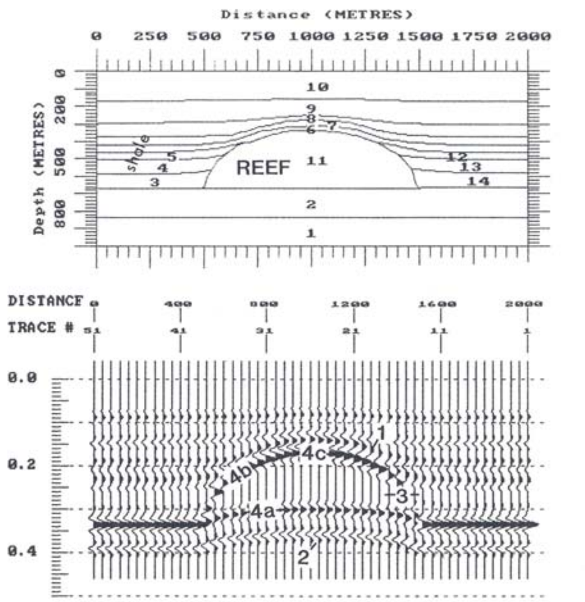
Pre-stack depth migration

Yan and Lines, *The Leading Edge*, (2001)

2.9.2.3 Reefs

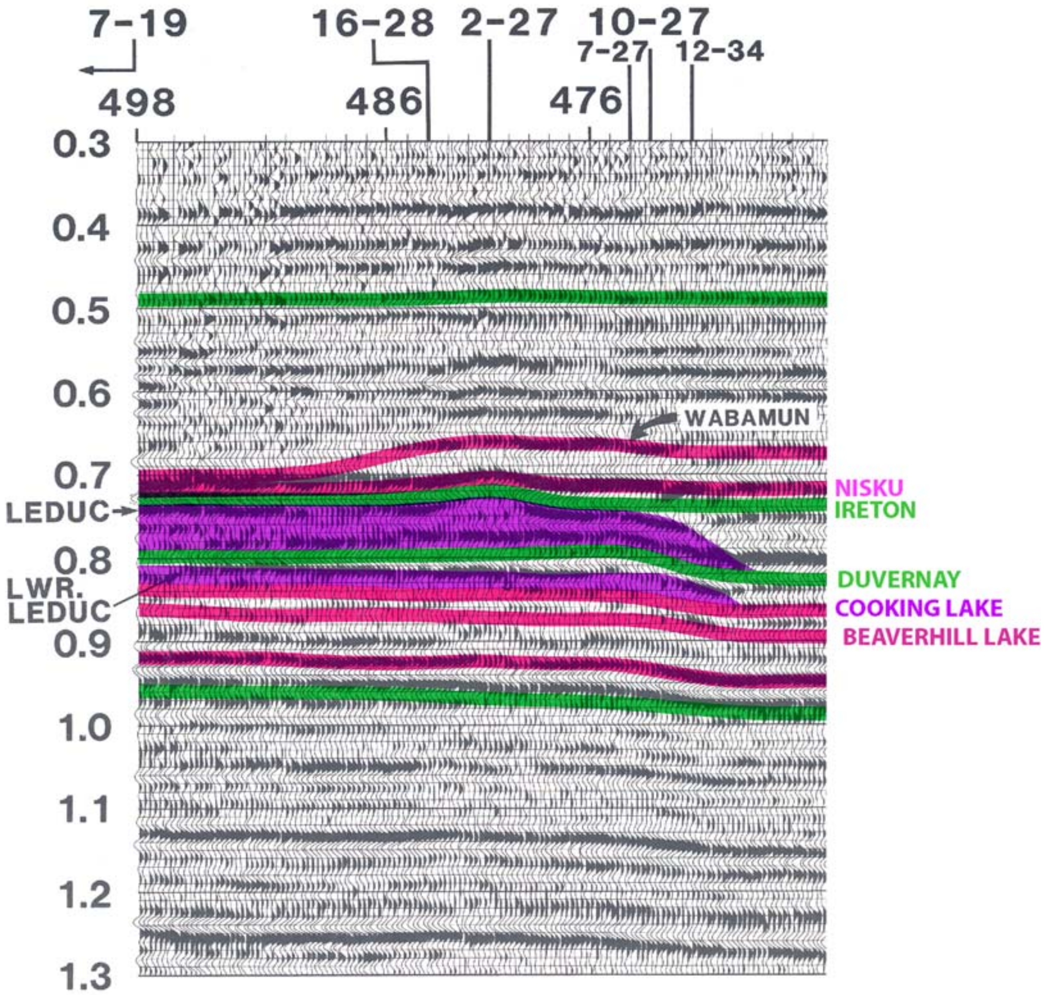
Reefs are often a zone of high porosity in a carbonate layer and make good hydrocarbon reservoirs. When exposed on the surface they can form spectacular topography, such as the Permian Reef in Guadalupe Mountains National Park (Texas). However, they are less spectacular on seismic data!

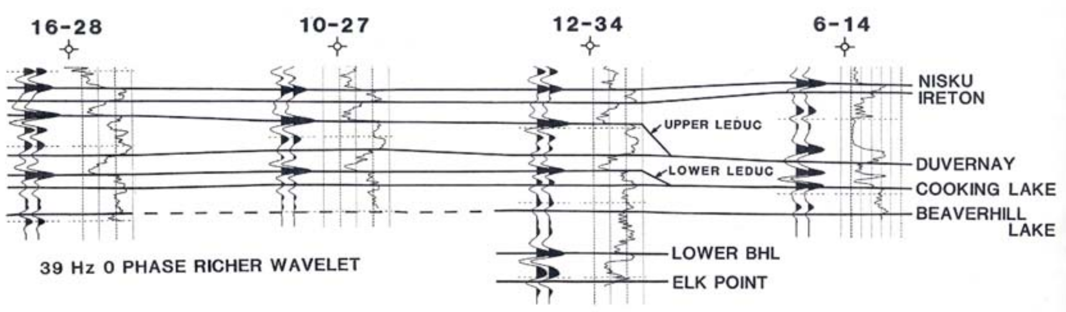
Leduc reefs



● Seismic characteristics of the reef are draping of overlying sediments and upper surface. Note also that the base of the reef does not appear as a flat feature. It is **pulled up** because of the higher velocity within the reef.

C2.9.2 Redwater Leduc reef



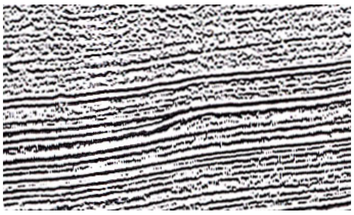


- Seismic section above is from the Redwater Leduc reef 40 km northeast of Edmonton. The reservoir is Devonian age carbonates, overlain by Ireton formation shales that provide a seal.

- Also note the base of the upper Leduc and Duvernay appears to rise under the reef. This is an example of **pull up.** The base is flat and appears at earlier TWTT since the velocities in the reef are higher than at the same depth east of the reef. This is also illustrated in the synthetic example on the left (*Andersen et al*., 1989, Chapter 1.)

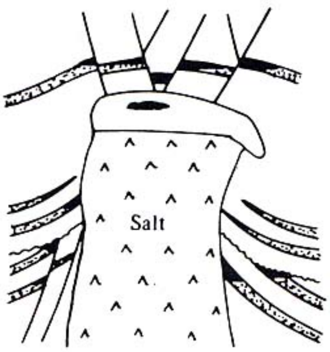
● Again, well logs are used to generate **synthetic seismograms**, which allow the interpretation of the seismic section. This will show which lithologic contrasts will dominate the seismic response. Allows the structure mapped in a well to be extrapolated away from the well in places where seismic data are available.

Louisiana and East Texas reefs

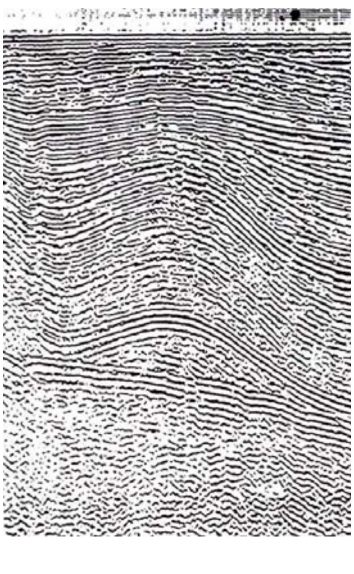


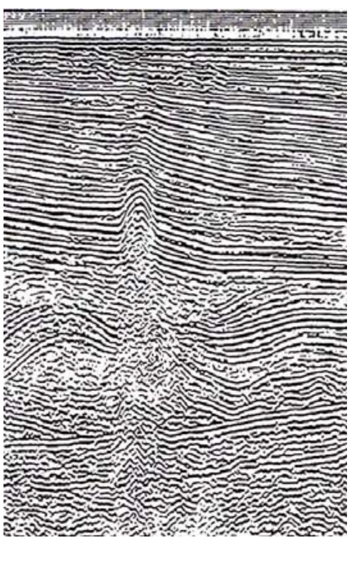
Telford 4.104, Telford 4.105

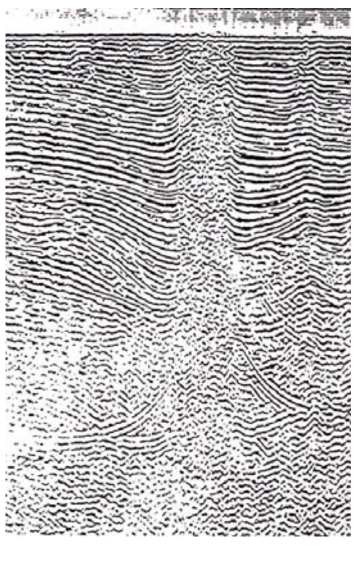
2.9.2.4 Salt related hydrocarbon reservoirs



Salt can produce significant hydrocarbon traps when sedimentary units are deformed in salt tectonics. Some of the earliest hydrocarbon deposits discovered with geophysics were associated with salt-domes, and were detected through gravity surveys with torsion balances and pendulums (Geophysics 224, Section B)

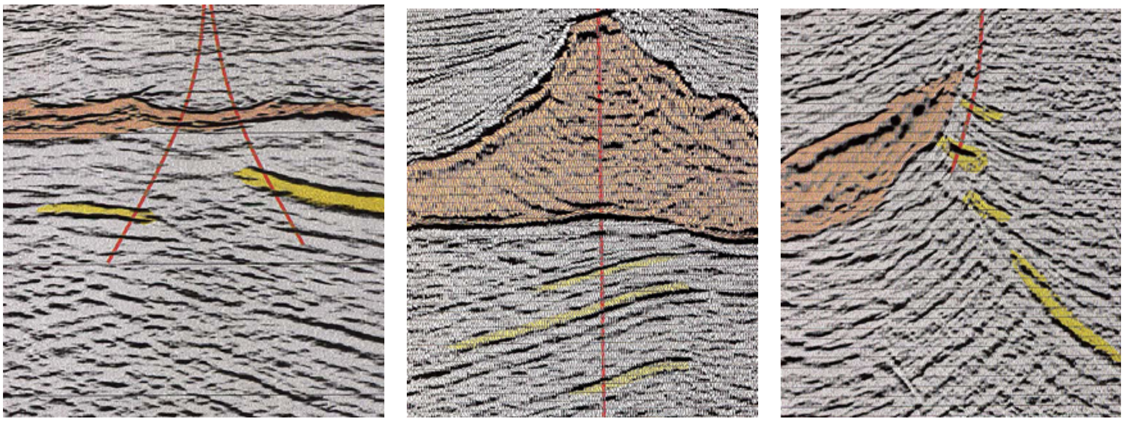






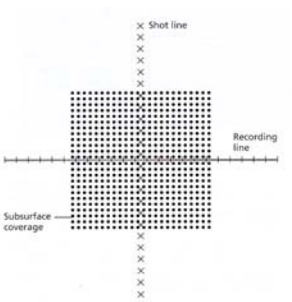
Salt creeps under mechanical loading and salt sheets can flow horizontally. Salt diapers can rise in a column to the surface. The figure above shows 4 second seismic reflection data that reveals the evolution of a salt sheet, progressing from a salt swell, to a diapir that penetrates the sediments, and finally to the surface *(North Sea, Telford figure 4.102)*

Hydrocarbon reservoirs may be located in the sedimentary sequence beneath a salt layer. However, the high velocity of a salt body makes it difficult to image these reservoirs.



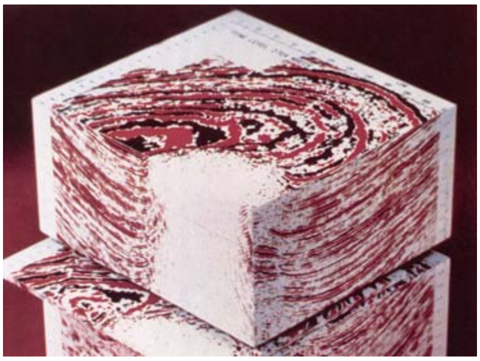
The examples above show the Enchilada, Hickory and Tanzanite sub-salt discoveries in the Gulf of Mexico, and are taken from an advert by Diamond Geophysical Service Corporation (*The Leading Edge*, November 1999) Brown denotes the salt body and yellow the reservoir. Imaging techniques such as pre-stack depth migration have made a big improvement in this type of exploration problem, as described in C2.8 for the Sigsbee dataset.

3-D seismic reflection surveys

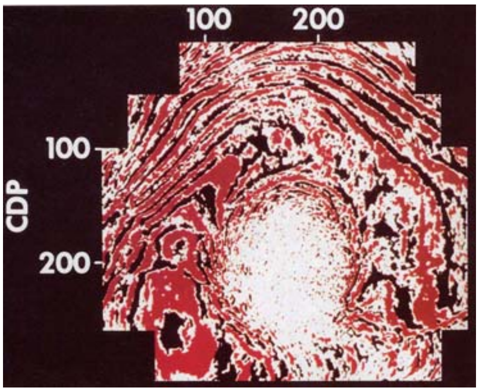


In a 3-D seismic survey data is recorded on a grid of surface lines. In land, the shot lines and recording lines are generally orthogonal. (*Kearey 4-34*). This produces a grid of CDP’s on a subsurface reflector.

In marine seismic surveys, an array of airguns and multiple streamers give a swarth of 3-D coverage (Kearey 4-36). Once 3-D data has been collected, it may displayed as a seismic data volume (seismic cube). A vertical slice corresponds to the depth sections we have discussed.



Three-dimensional seismic data volume (*seismic data cube*) collected over a salt dome in the Gulf of Mexico. Kearey Plate 4.1. Colour corresponds to amplitude of reflection.

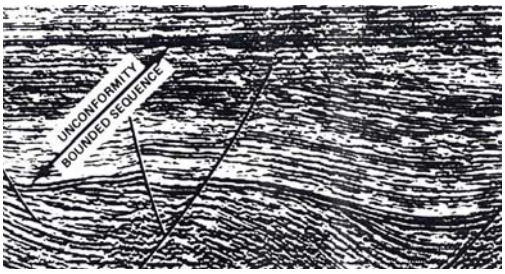


A time slice (*seiscrop section*) from the above data volume at 3.7 seconds. At each CDP the amplitude of the trace is plotted in colour. Note that changes red-black correspond to positive-negative arrivals (layers). Steeply dipping layers produce closely spaced +/- changes.

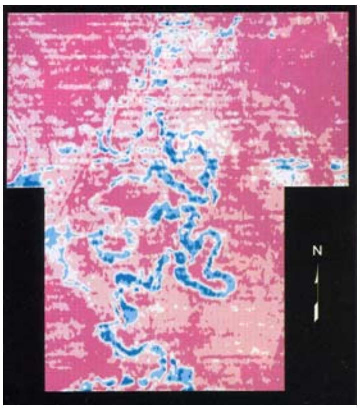
Time-structure maps – maps depth to reflector in time (*e.g. Kearey 4.47*)
Structural contour maps - maps depth to reflector in depth
Isochron maps – shows variation of layer thickness as function of time
Isopach maps - layer thickness in metres

Other interpretational techniques and concepts

Seismic stratigraphy – relate the seismically imaged sedimentary sequence to depositional history. Locate unconformities etc.



Seismic facies analysis. Use of the reflection geometry and character to determine the sedimentary facies. This can reveal the environment in which sedimentary rocks were deposited. Can help identify potential source rocks, seals and reservoir rocks.



Sometimes 3-D surveys can show paleo river channels in time slices. In this location a particular reflector is deeper over the river channel and at a given time, this will give a different reflection amplitude on CDP's that are within/outside the channel. *Kearey Plate 4.4*

C2.9.3 Recent developments in hydrocarbon exploration with seismic reflection

2.9.3.1 Pre-stack depth migration.

- Now possible with the increased computing power that is available for processing seismic data. With steeply dipping structures, this technique is much better at imaging than post-stack depth migration schemes.

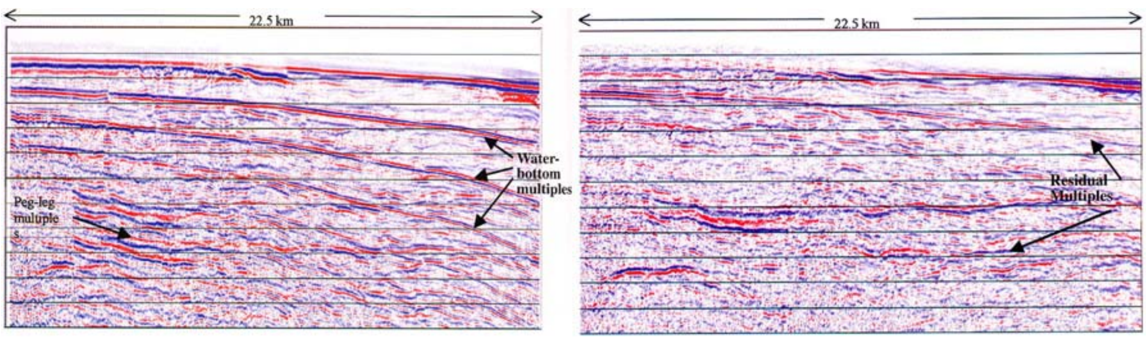
The Leading Edge, **21**, Special section PSDM 2, The Sequel, December 2002.

2.9.3.2 Marine exploration

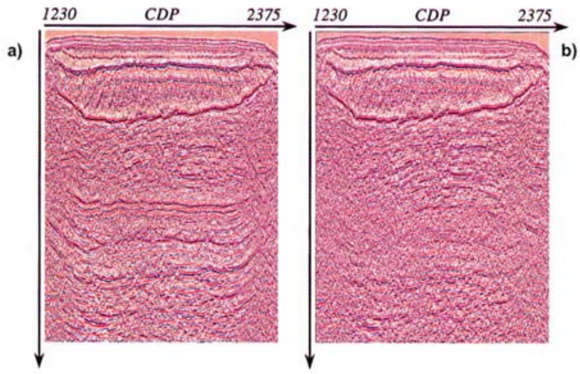
- Concerns about the possible effects of air gun noise on marine mammals has intensified in recent years. Details described by *Gausland*, 2000.

2.9.3.3 Multiple attenuation.

Multiples can obscure later arrivals in reflection data. Various processing techniques can be used to remove them. *Matson et al.,* (1999) give a comparison of various methods.



Left - Multiples in data from the Canarvon basin (Australia) from *Matson et al.,* (2001). *Right* – section after the most convincing multiple suppression technique was applied. Vertical scale is 0 to 1.2 seconds



Pre-stack depth migrated images before and after multiple removal. Vertical scale is 1200 to 6800 m. Subsalt geology is definitely visible after multiple removal. From *Guitton* (1999).

● what will be the repeat times of multiples in 1 km of water? In 2 km? v_w= 1500 m/s

● S-wave data can have less problems with multiples than P-wave data? Why?

2.9.3.4 Amplitude versus offset

● State-of-the-art :*The Leading Edge*, **19**, Special section AVO, November 2000.

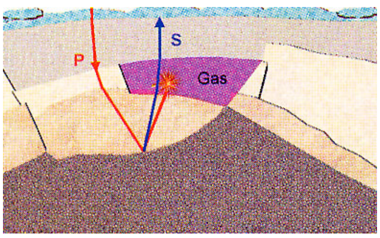
● AVO doesn't always work! Some cautionary tales from *Allen et al*, (1993)

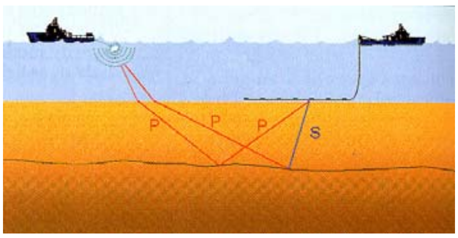
2.9.3.5 Shear waves and seafloor recording

● 3-component (3-C) recording allow S-waves to be recorded included in the analysis. This requires **seafloor** seismic recording in marine surveys since S-waves cannot travel through the water column. The converted phase is sometimes called a C-wave.

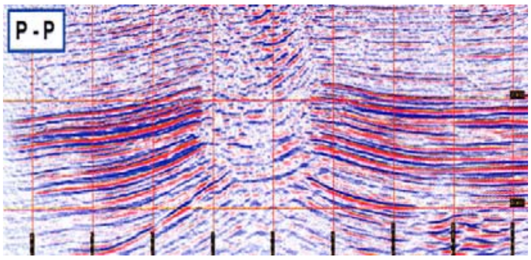
● Use either ocean bottom seismometer (OBS) or ocean bottom cables (OBC). These can be laid in a fixed location on the seafloor, or dragged by the survey ship.

● S-waves are generated by P-to-S conversion at the reflector. This requires non-normal incidence, so large source-receiver offsets are used.

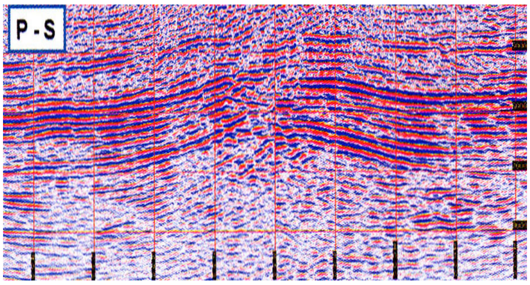




Imaging through gas clouds

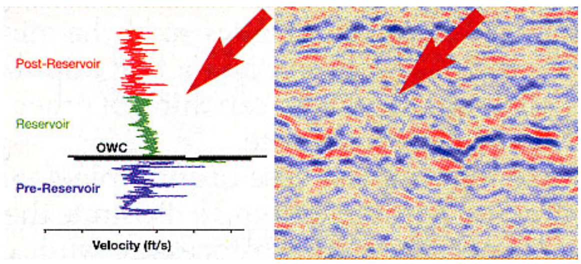


Seismic reflection image of an anticline in the Tommeliten Field, Norwegian sector of the North Sea. Gas escaping from the reservoir forms a gas chimney, which attenuates the P-waves. This occurs because P-waves are sensitive to the compressibility of gas in pore spaces. In contrast, S-waves do not compress the rock as they travel through a rock unit. From *Caldwell* (1999)

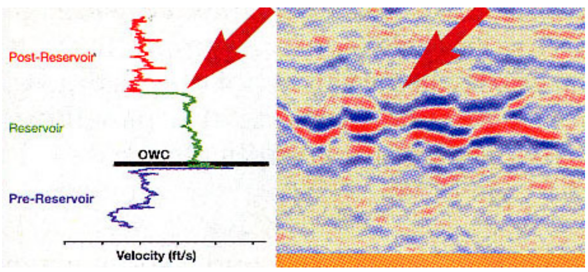


The same structure imaged with the arrival of S-waves produced by P-to-S conversion at depth. These waves are significantly less attenuated by the gas cloud and the top of the anticline is well imaged.

Some reservoirs have no P-wave expression



Towed streamer data (P-waves)

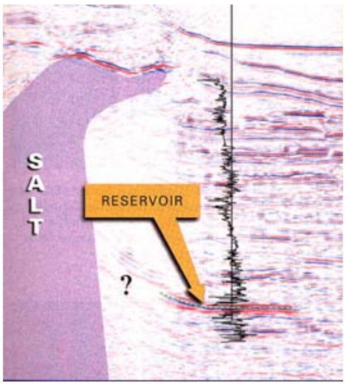


Ocean bottom cable (S-waves)

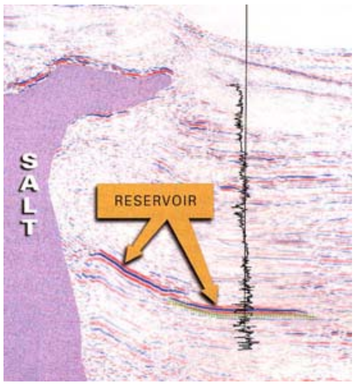
In the Alba Field (North Sea) the reservoir sands are overlain by a shale cap rock. The change in P-wave velocity is small at the top of the reservoir, and it is not imaged on the P-wave section. However there is an increase in S-wave velocity that produces a strong reflection (*Caldwell*, 1999).

Better illumination of high angle interfaces

- Seafloor recording of P-waves and S-waves can also give wider angle data coverage. This can improve illumination of targets. Example from Mississippi canyon, Gulf of Mexico, PGS advert, *The Leading Edge*, **20**, 28, January 2001



Towed streamer



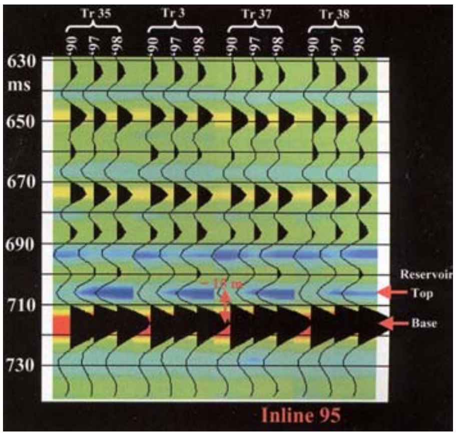
Seafloor cable

The Leading Edge, **18**, Special section : Multi-component offshore, *November 1999*
The Leading Edge, **20**, Special section : Advances in shear wave technology, *September 2001.*

<u>2.9.3.6 Detecting time variations in hydrocarbon reservoirs during production</u>

- Repeat seismic survey at same location to determine **time variations** during production (time lapse or 4-D seismics)

- Need very careful processing to make an objective comparison between surveys. Ideally use exactly the same source and geophones. In some cases, the geophones are left in place between surveys. **Cross-equalization** is a processing technique that looks at events in trace that are not associated with the reservoir and seeks to equalize them over time.



Example from steam flood of a heavy oil reservoir at East Senlac SK. The survey was repeated in 1990, 1997 and 1998. Unfortunately different seismic sources and geophones were used in each survey, so an objective comparison is complicated (Li *et al*., 2001).

These results suggest that the negative polarity event at the top of the reservoir becomes stronger over time as steam heats the reservoir (maybe????)

● What other factors than the reservoir could change seismic data recorded at the same location in different surveys?

● Differencing of seismic sections. Kearey 4.41 shows time sections before and after gas was injected into a reservoir for storage.

● Kearey 4.42. Steam injection at a well in Duri oilfield, Indonesia. Base of reservoir initially shows pull-up and then push-down (sag). What does this tell us about the velocity in the reservoir during the injection?

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Geophysics 224 MJU 2006