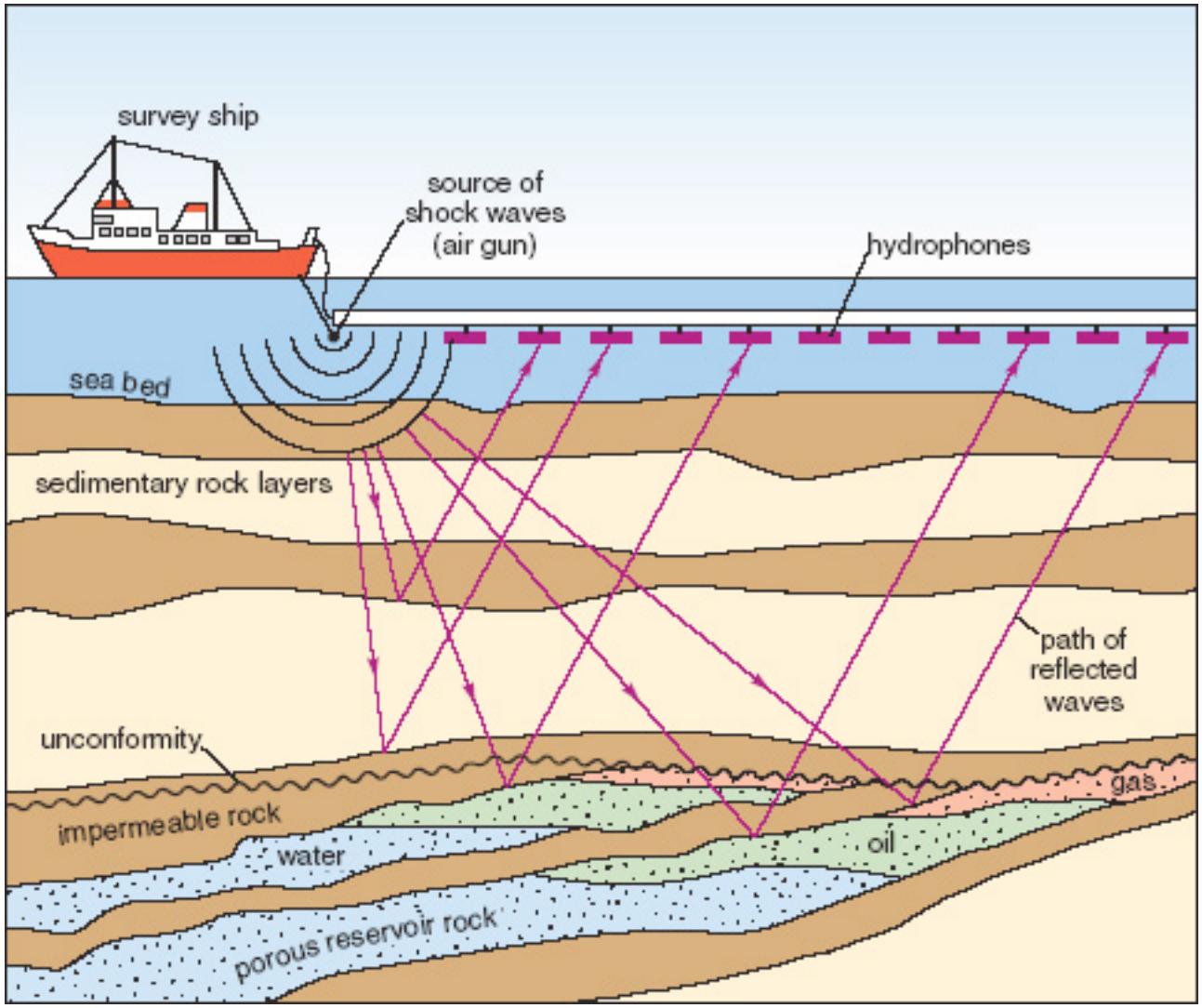
Reflection seismology

- Probe Earth's internal structure by examining energy reflected from subsurface layers
- Large number of sources/receivers regularly spaced
- Accuracy comes at the expense of processing complexity
- Usually limited to travel time, not amplitude

Oil exploration is an expensive, high-risk operation. Offshore and remote area exploration is generally only undertaken by very large corporations or national governments. Typical Shallow shelf oil wells (e.g. North sea) cost USD$10 - 30 Million, while deep water wells can cost up to USD$100 million plus. Hundreds of smaller companies search for onshore hydrocarbon deposits worldwide, with some wells costing as little as USD$100,000.

Offshore drilling has 20% success rate!


survey ship
source of
shock waves
(air gun)
hydrophones
sea bed
sedimentary rock layers
path of
reflected
waves
unconformity
gas
impermeable rock
water
oil
porous reservoir rock

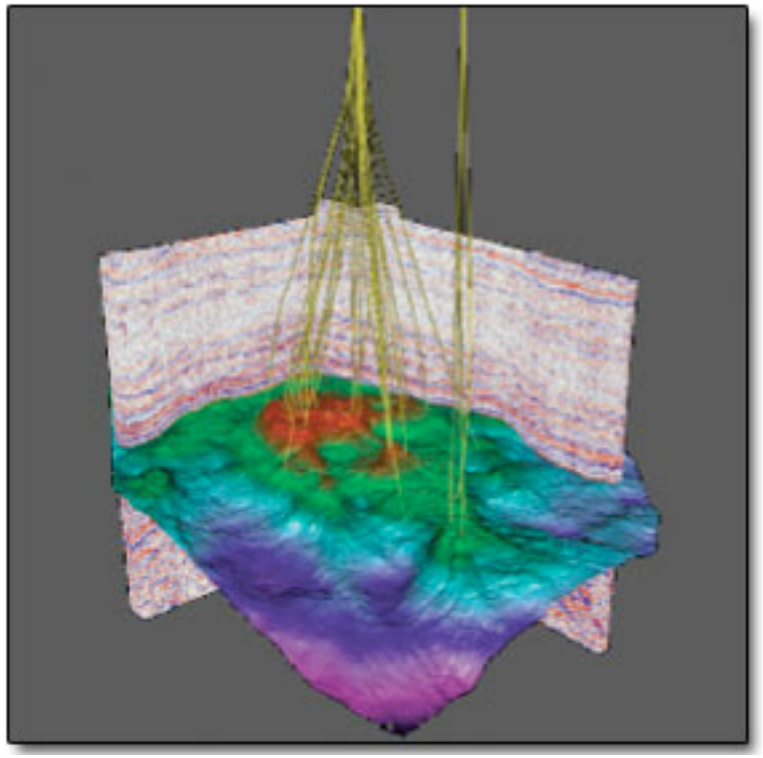
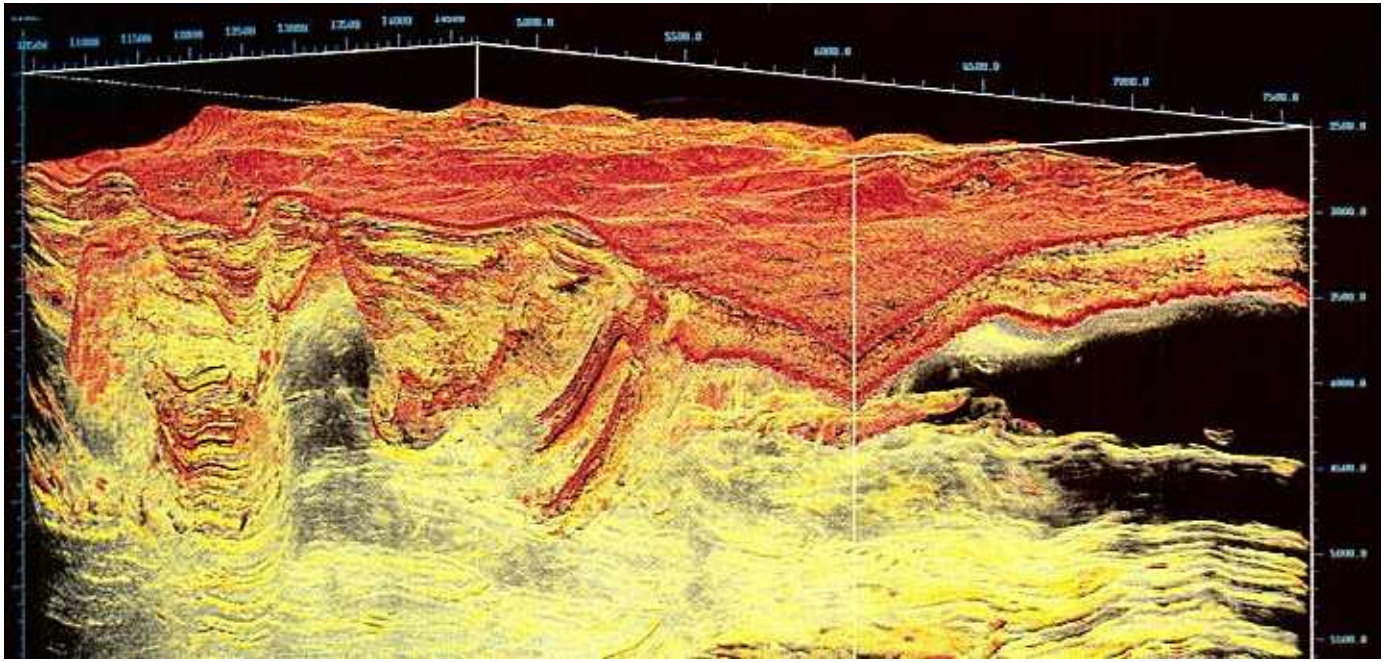


Figure 7: A 3-D view of the Palaeocene reservoir in the Nelson Field, North Sea. The image is derived from a 'cube' of closely spaced 3-D seismic data, onto which the paths of the production wells are superimposed. Bright colours in this perspective view relate to depths to a particular reflecting boundary. Reds and greens are structurally highest, where petroleum may be trapped.

3-D EXPLORATION SEISMOLOGY



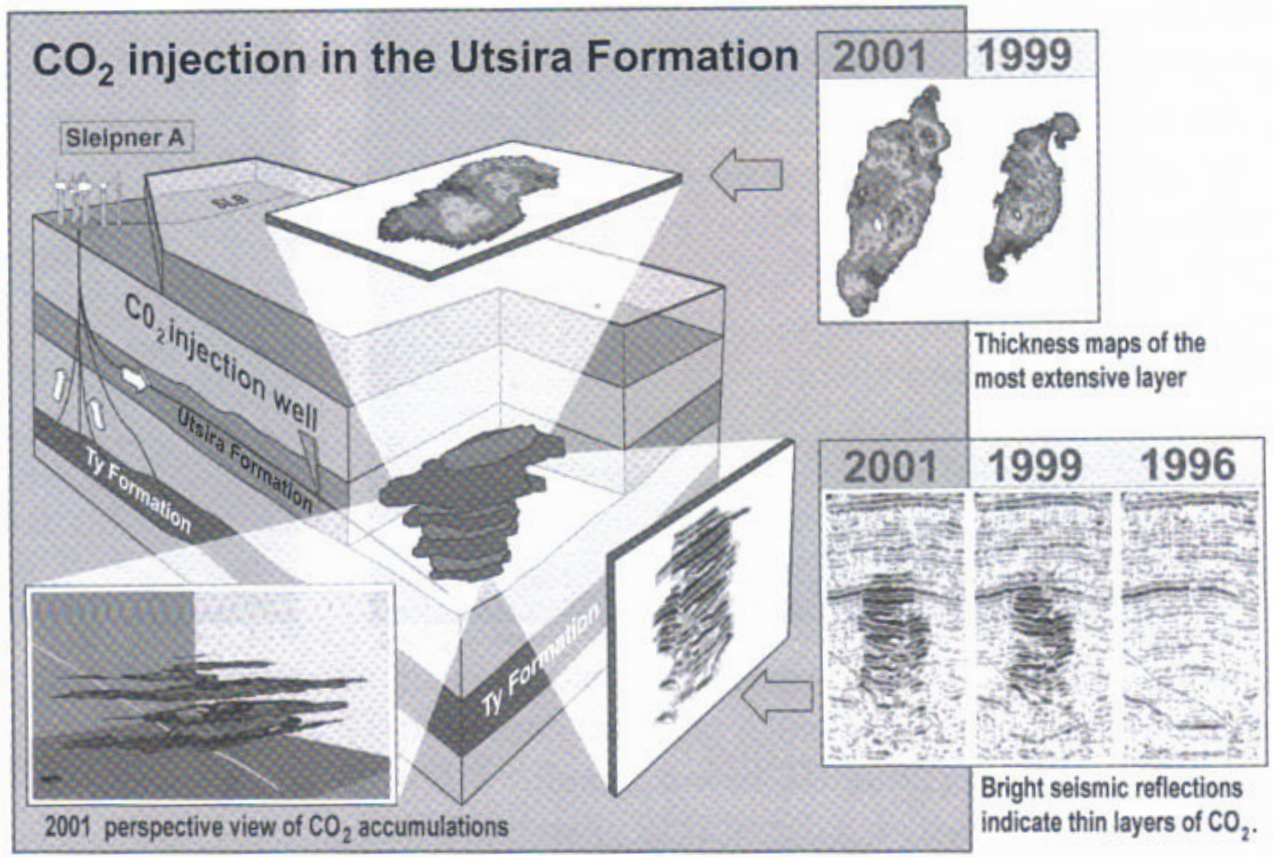
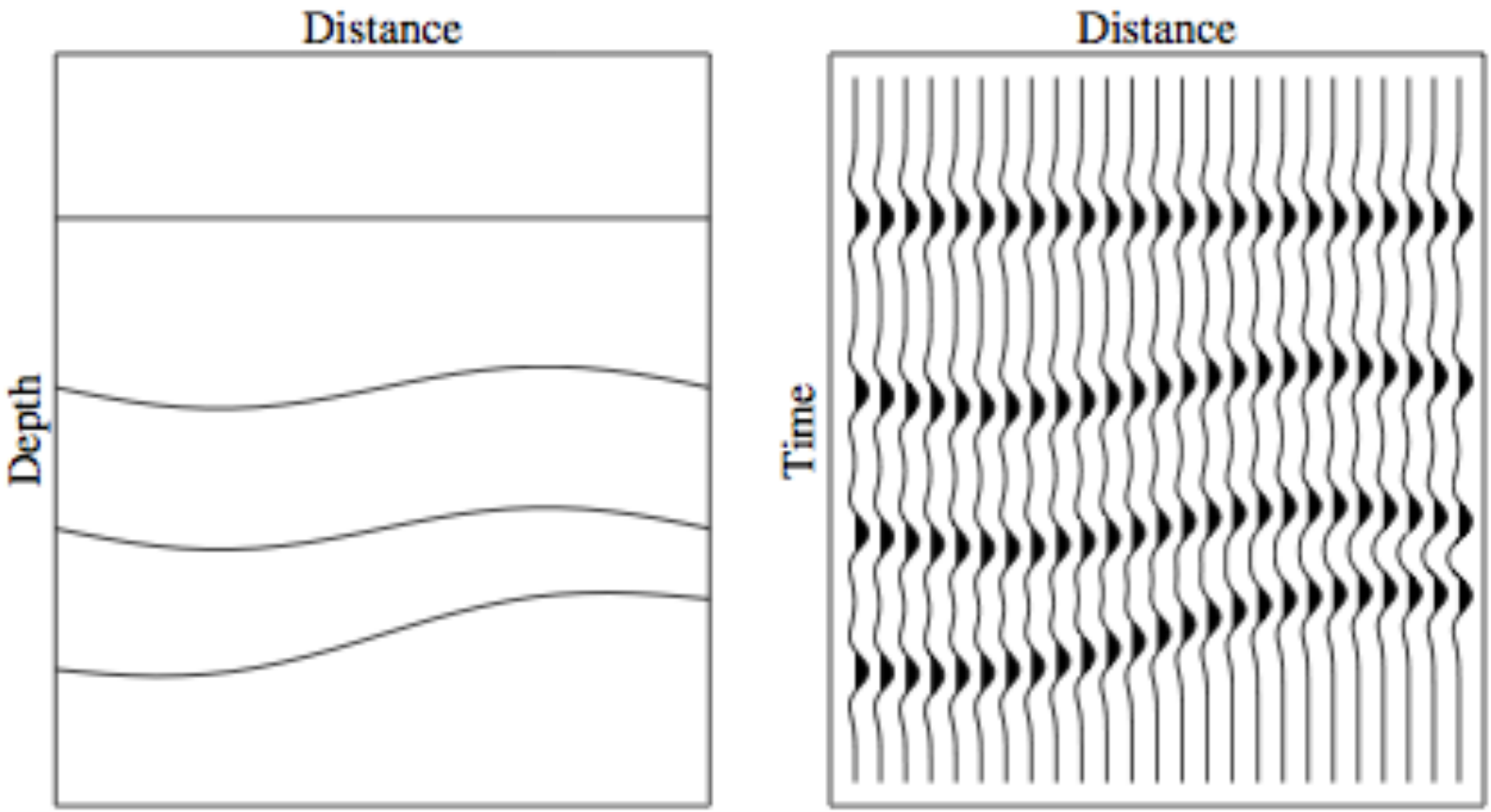


FIGURE 7.40. Block diagram illustrating the principle of CO_2 sequestration. Unwanted CO_2 produced with gas from the Sleipner field Ty Formation is injected into the Utsira Formation repository. The 1999 and 2001 time-lapse seismic sections (lower right) show that the injected CO_2 is in place and that the volume has increased substantially. This is corroborated by thickness maps of the most extensive layer (upper right). The 1996 survey was made prior to CO_2 injection; the 1999 and 2001 surveys were made during CO_2 injection. (Courtesy of Statoil ASA.)

Zero-offset sections



Zero-offset sections

- Variety of source-receiver offsets, processed to produce an equivalent zero-offset section
- Averaging (*stacking*) the records to increase SNR
- Layer spacing short compared to source duration → *deconvolution*
- Lateral variations/dipping reflectors results in scattered energy → *migration*
- Errors in velocity model will affect stacking or migration processing

P-S data

- S waves travel only in solid (NOT underwater), thus are inaccessible with conventional survey
- Bottom receivers (OBS, OBC) are equipped with geophones that lie on the seafloor → measure PS waves (converted waves)
- PS waves are less affected by gas
- Needs larger offset for ensuring P waves to travel downward outside the gas region

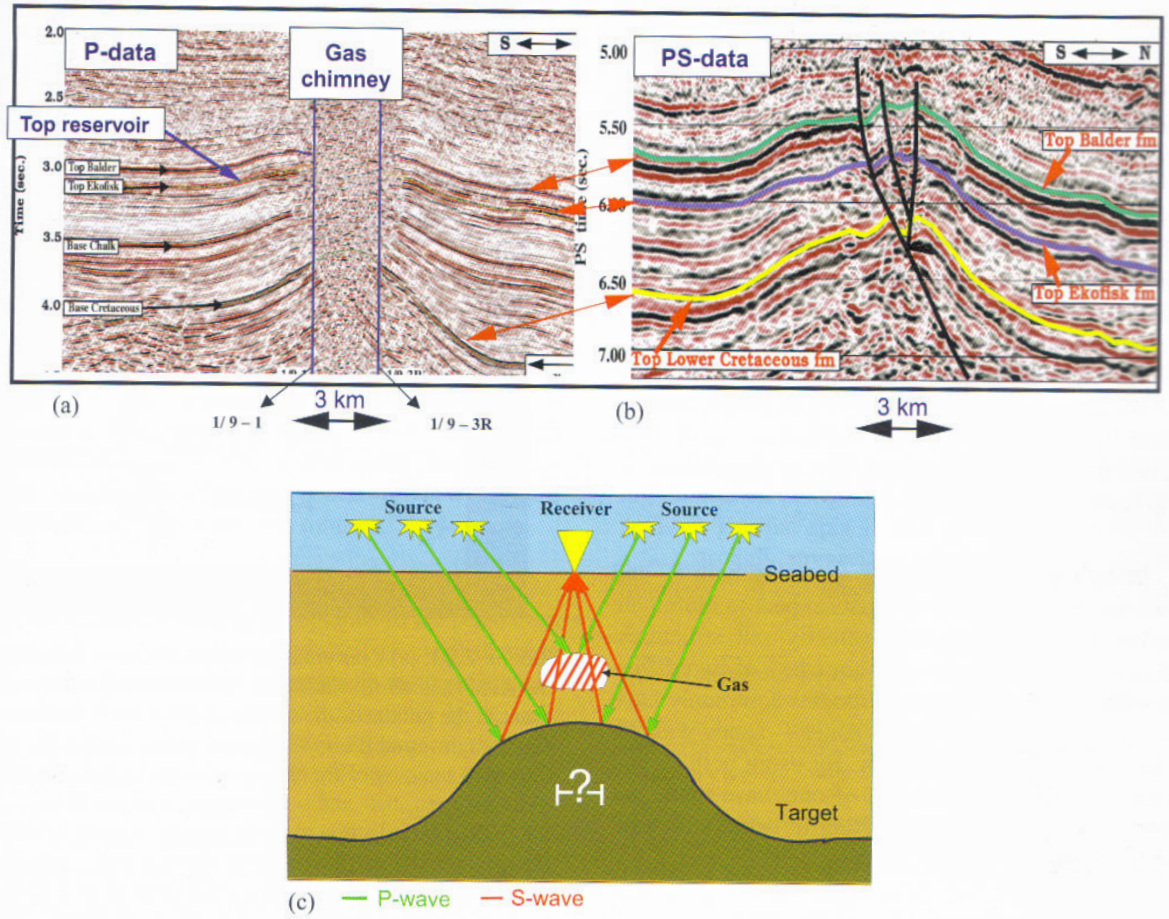


FIGURE 7.33. (a) On the conventional P-wave section, the Tommeliten Alpha structure is obscured by gas escaping through shale (a gas chimney). Consequently, over a horizontal distance of 3 km between well 1/9-1 (left vertical line) and well 1/9-3R (right vertical line) the top of the structure cannot be mapped. (b) The PS-data considerably reduce the area of uncertain structural interpretation, especially in the deeper part of the section (top Ekofisk Formation and top Lower Cretaceous Formation). (c) Illustration of the principle of undershooting gas areas by PS-waves. The target (reservoir) is in the dome, with a gas cloud in the red-striped white area. The yellow triangle on the seabed represents the 4C sensor. Where downgoing P-waves (green arrows) travel outside the gas-affected area, good quality PS-waves (red arrows) are generated, traveling upward to the sensor. The gas area has little effect on S-waves, because they are largely unaffected by gas. Where downgoing P-waves travel inside the gas-affected area, they are attenuated severely, and no significant PS-waves are generated from the target. Thus, to obtain high-quality PS images of reservoirs below sediments or rocks charged with gas, we must ensure that the offsets (source-receiver distances) are large enough for P-waves to travel downward outside the gas area. (Courtesy of Statoil ASA.)

North Sea Gas Chimney

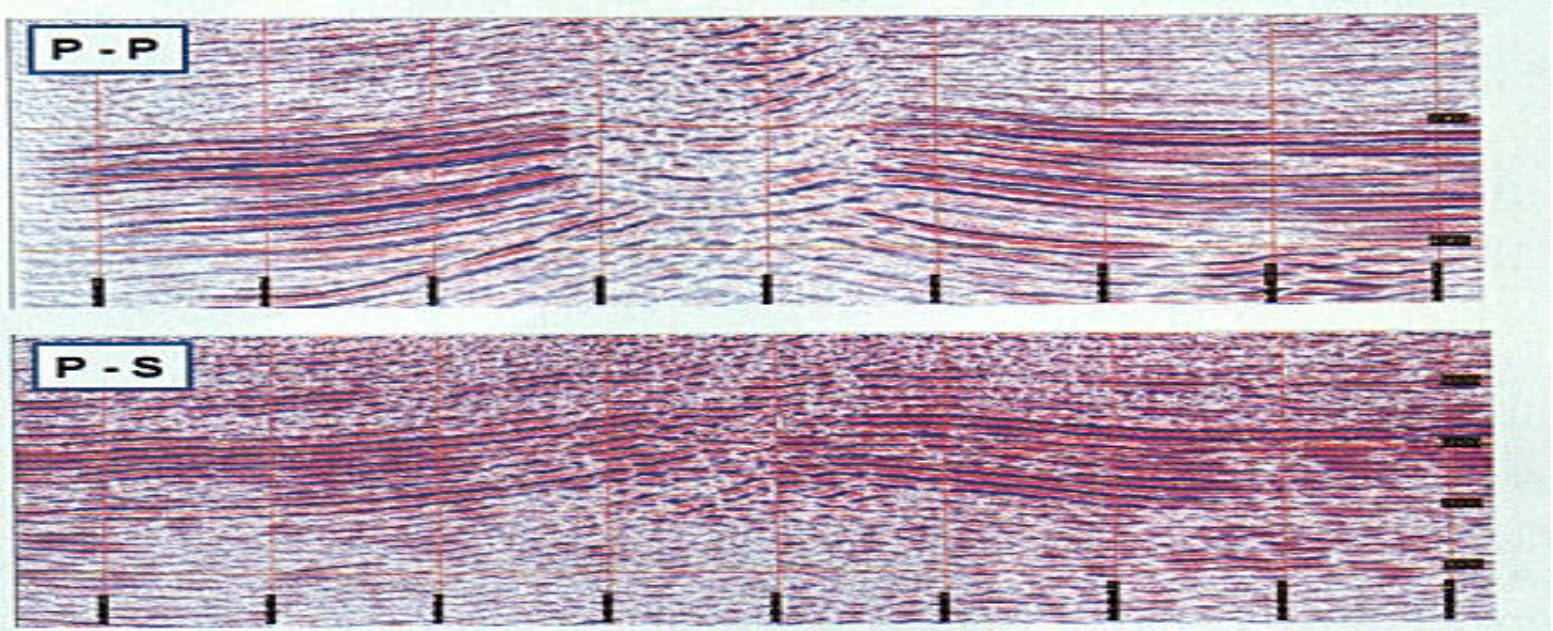


Figure 5. This example is from the Tommeliten Field in the Norwegian sector of the North Sea, courtesy of Statoil. It is one of the earliest examples that demonstrated the usefulness of *PS*-wave data compared to *PP* for imaging through a gas cloud. Note how the gas chimney disrupts the *P*-wave (upper section), while allowing the *S*-wave (lower section) energy to generate a useful image beneath the gas chimney.

CMP stacking

Normal move out (NMO)

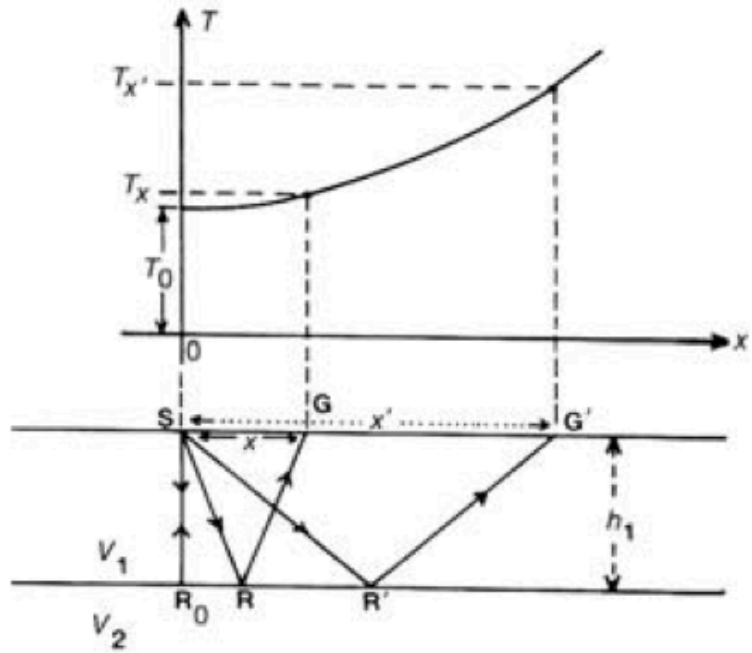
The hyperbolae shaped reflection is referred to at the **normal move out**

$$T_x = \frac{2SR}{V_1} = \frac{2}{V_1}\sqrt{h_1^2 + \left(x/2\right)^2}$$

or

$$T_x^2 = T_0^2 + \frac{x^2}{V_1}$$

➔ a hyperbolae



The importance of NMO

- Having determined the layer velocity, we can use the predicted quadratic shape to identify reflectors
- Then correct (shift traces) and stack to enhance signal to noise

$$\Delta T_{NMO} = T_x - T_0 \approx \frac{x^2}{2T_0V_1^2}$$

CMP stacking and NMO

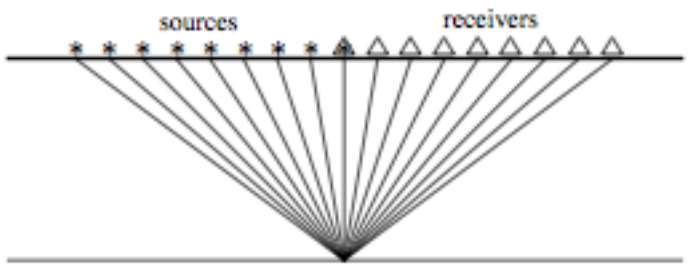


Figure 7.4: The source and receiver locations for a common midpoint (CMP) gather.

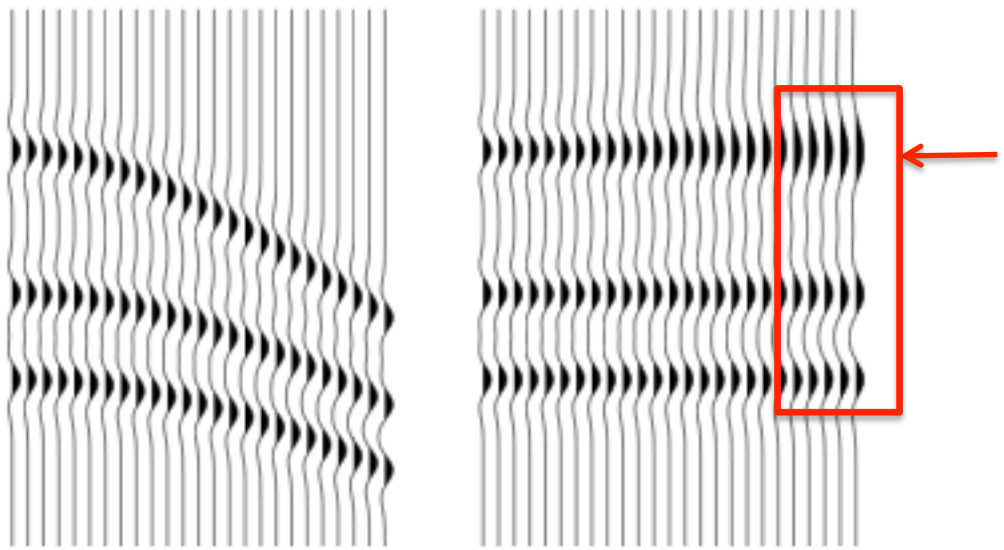


Figure 7.5: The left plot shows reflection seismograms at increasing source–receiver distance. The right plot shows the same profile after applying a NMO correction to each time series. Note that this removes the range dependence in the arrival times. The NMO corrected records can then be stacked to produce a single composite zero-offset record.

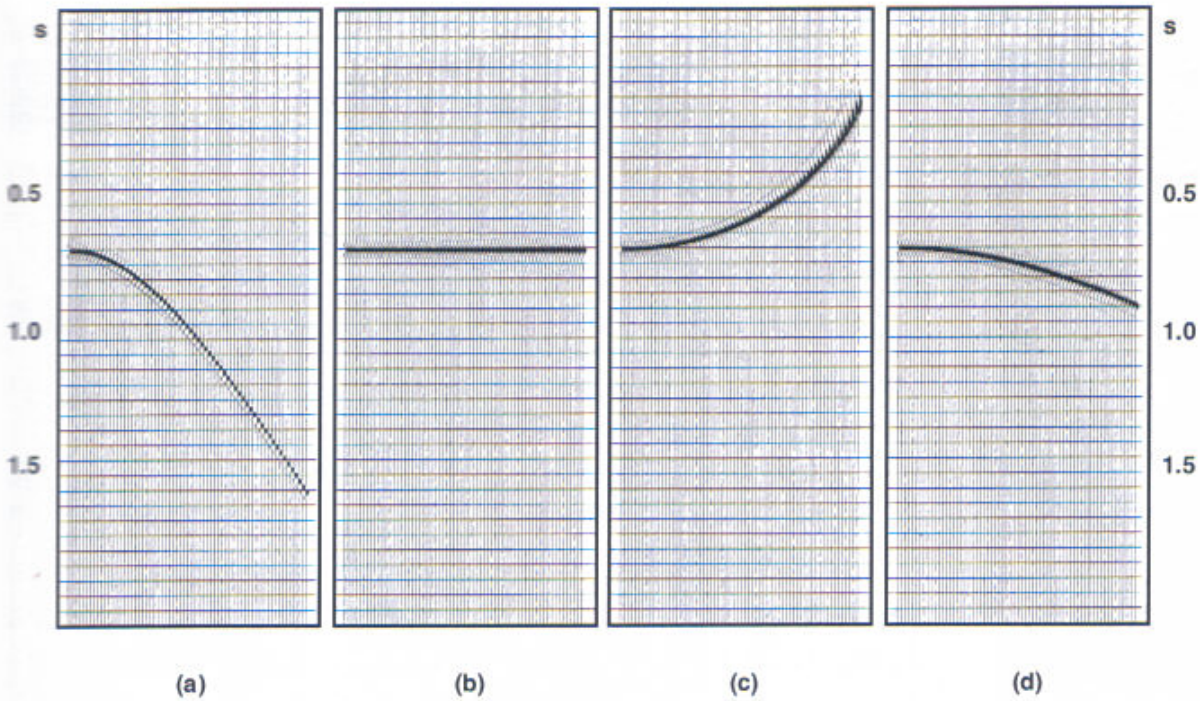


FIGURE 11.46. (a) CMP gather containing a single event with a moveout velocity of 2264 m/s. (b) NMO-corrected gather using the appropriate moveout velocity. (c) Overcorrection because the velocity (2000 m/s) used was too low. (d) Undercorrection because the velocity (2500 m/s) used was too high. (Adapted from Yilmaz, 1987.)

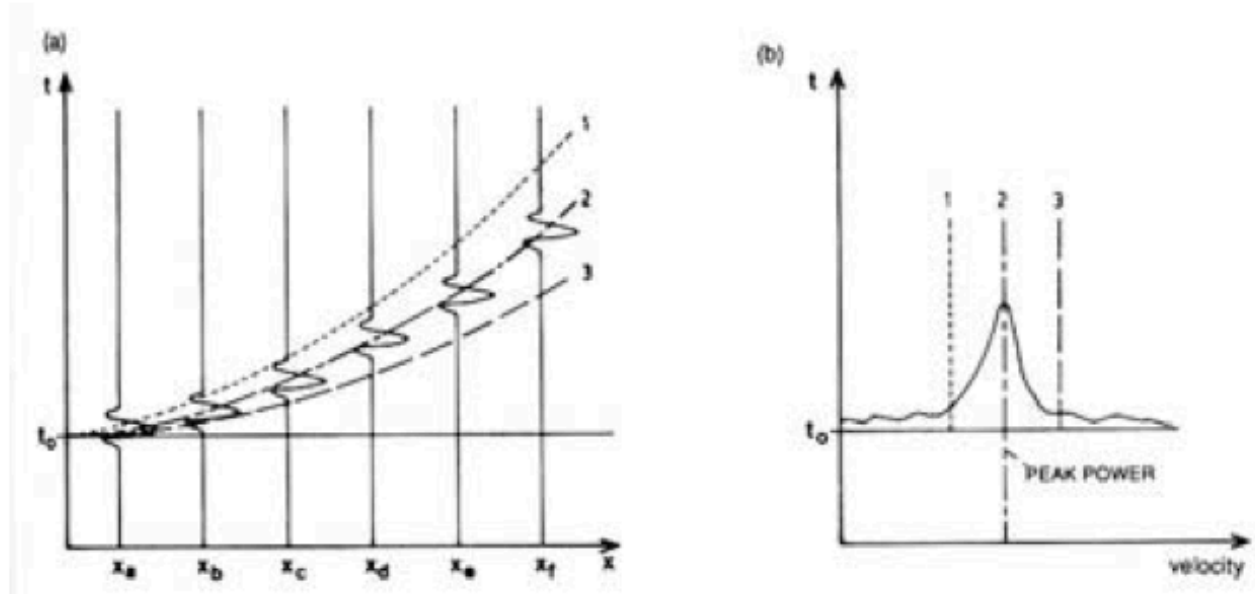
Stacking velocity

In order to stack the waveforms we need to know the velocity. We find the velocity by trial and error:

$$\Delta t_{NMO} = \frac{x^2}{2\alpha_1^2 t_0}$$

- For each velocity we calculate the hyperbolae and stack the waveforms
- The correct velocity will stack the reflections on top of one another
- So, we choose the velocity which produces the most power in the stack

V_2 causes the waveforms to stack on top of one another



Stacking velocity

Multiple layer case

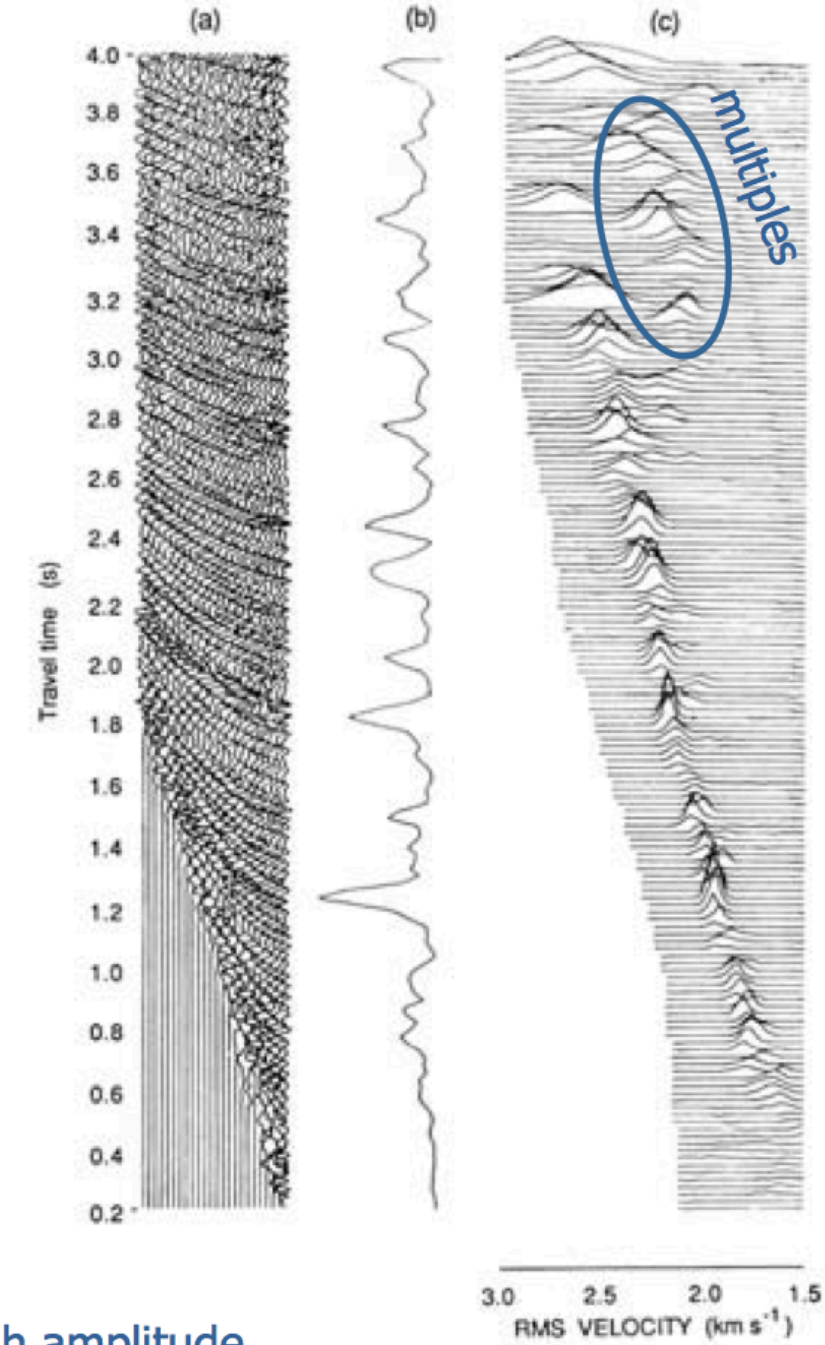
A stack of multiple horizontal layers is a more realistic approximation to the Earth

- Can trace rays through the stack using Snell's Law (the ray parameter)
- For near-normal incidence the moveout continues to be a hyperbolae
- The shape of the hyperbolae is related to the time-weighted rms velocity above the reflector

➔ Generate a velocity spectrum

➔ Pick stacking velocities

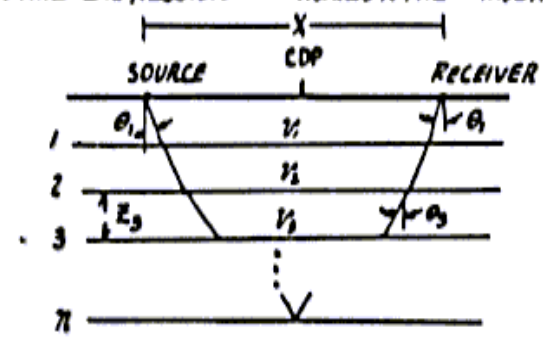
The **interval velocity** can be determined from the rms velocities layer by layer starting at the top



Multiples: When two velocities produce a high amplitude stack one is probably a multiple

This summary slide shows that the only item changing in the definition of the reflection equation is the definition of V_{nmo}.

TIME EXPRESSION – HORIZONTAL MULTILAYERS



Alternate Method: TAYLOR SERIES EXPANSION

$$T_{x,n}^2 = T_{0,n}^2 + \frac{x^2}{V_{RMS,n}^2} + \cdots \text{H.O. terms.}$$

$$V_{RMS,n}^2 = \sum_{i=1}^{n} v_i^2 \Delta t_i \Big/ \sum_{i=1}^{n} \Delta t_i$$

SUMMARY OF VELOCITY NMO EQUATIONS

STRUCTURE		EQUATION	$V_{NMO} \overset{?}{=} f(v_i)$
	HORIZONTAL SINGLE LAYER	$T_x^2 = T_0^2 + \frac{x^2}{V_{NMO}^2}$	V_{NMO} = INTERVAL VELOCITY
	DIPPING SINGLE LAYER		$V_{NMO} = \frac{v_1}{\cos\alpha}$
	HORIZONTAL MULTI LAYERS		$V_{NMO} \cong V_{RMS}$ $V_{RMS}^2 = \frac{\sum_{i=1}^{n} v_i^2 \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}$
	DIPPING, PARALLEL MULTI LAYERS		$V_{NMO} \cong \frac{V_{RMS}}{\cos\alpha}$
	DIPPING, NONPARALLEL MULTI LAYERS		ITERATIVE RAY TRACING PROBLEM

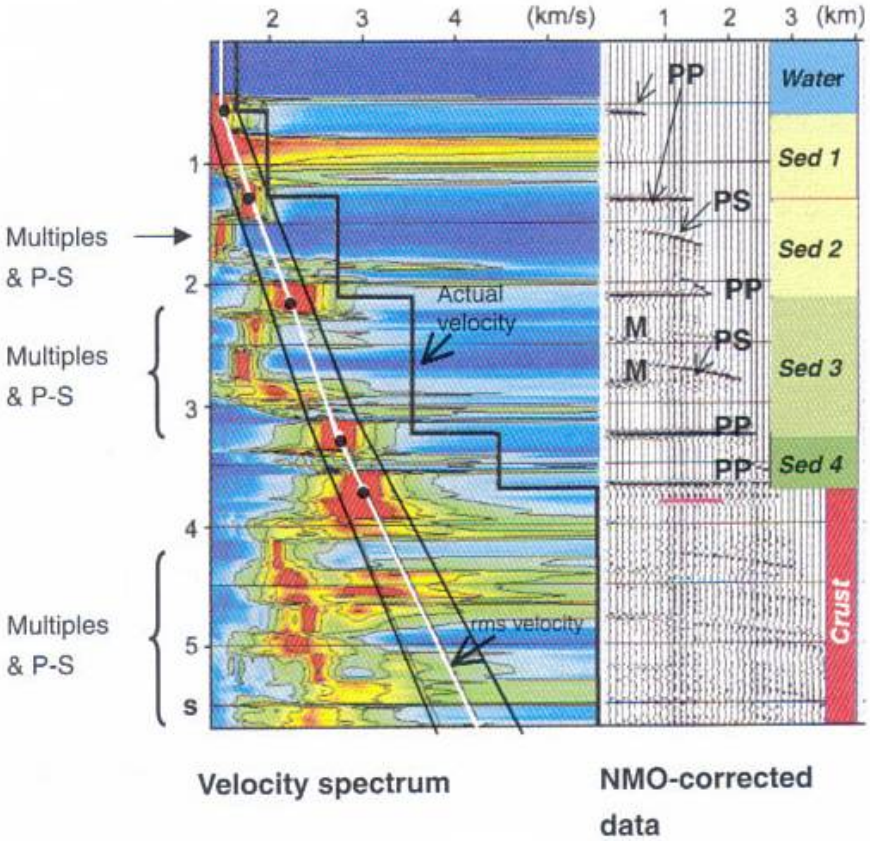


FIGURE 11.48. Velocity semblance plot. Velocity analysis of finite-difference modeled data. The model is superimposed on the CMP gather. Note how the velocity analysis shows a good fit between the semblance peaks (red) and the theoretically computed rms velocities (black dots superimposed on a white curve). PP indicates P-to-P reflection, PS and P-S indicate P-to-S reflections.

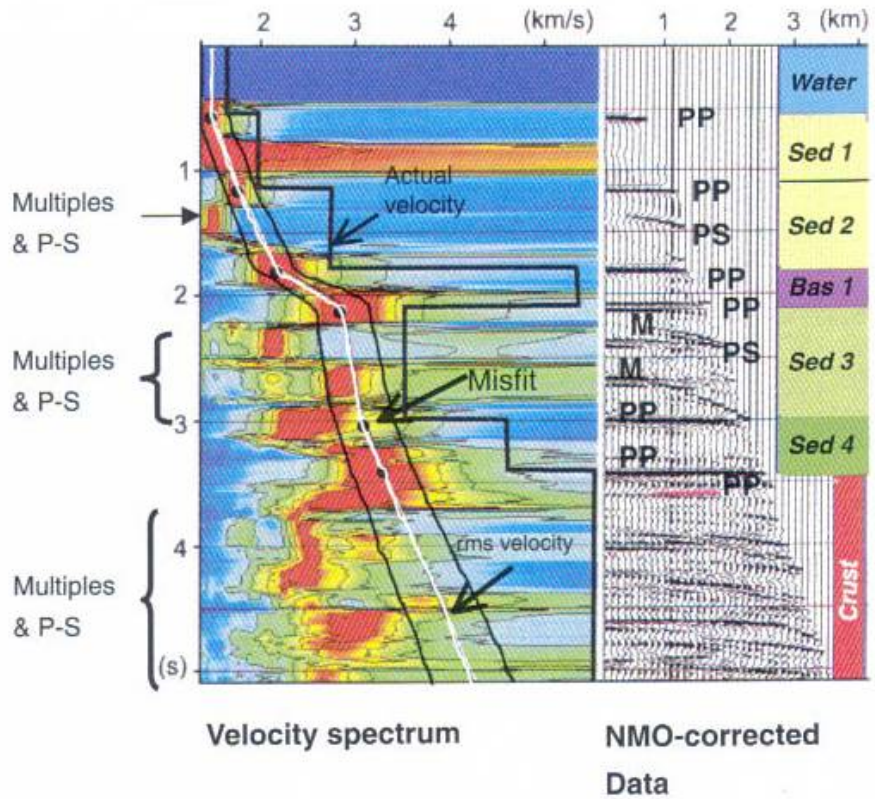
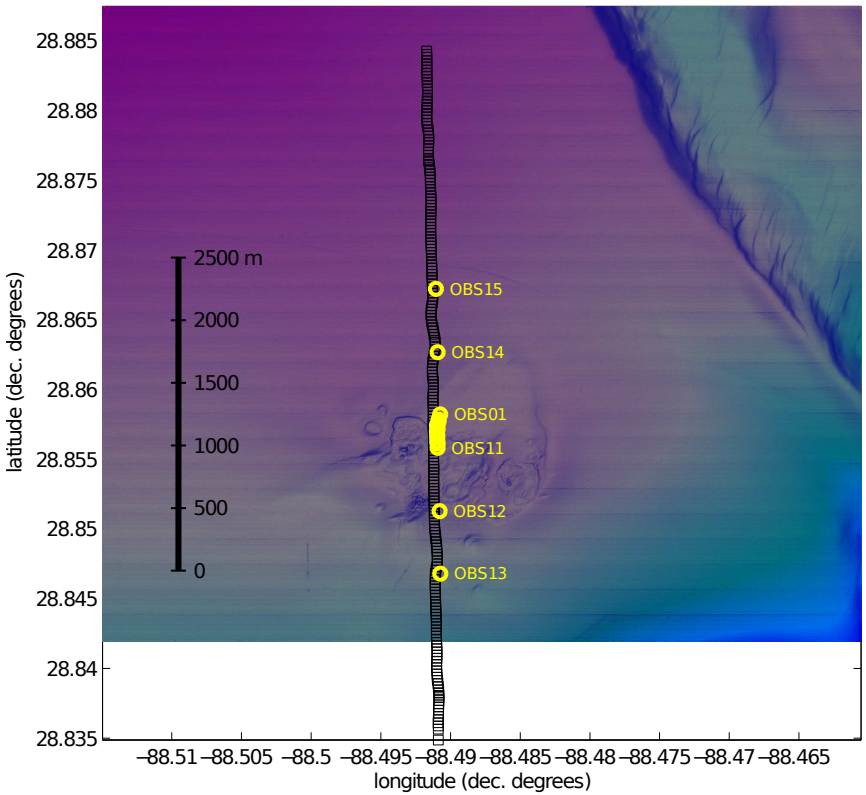
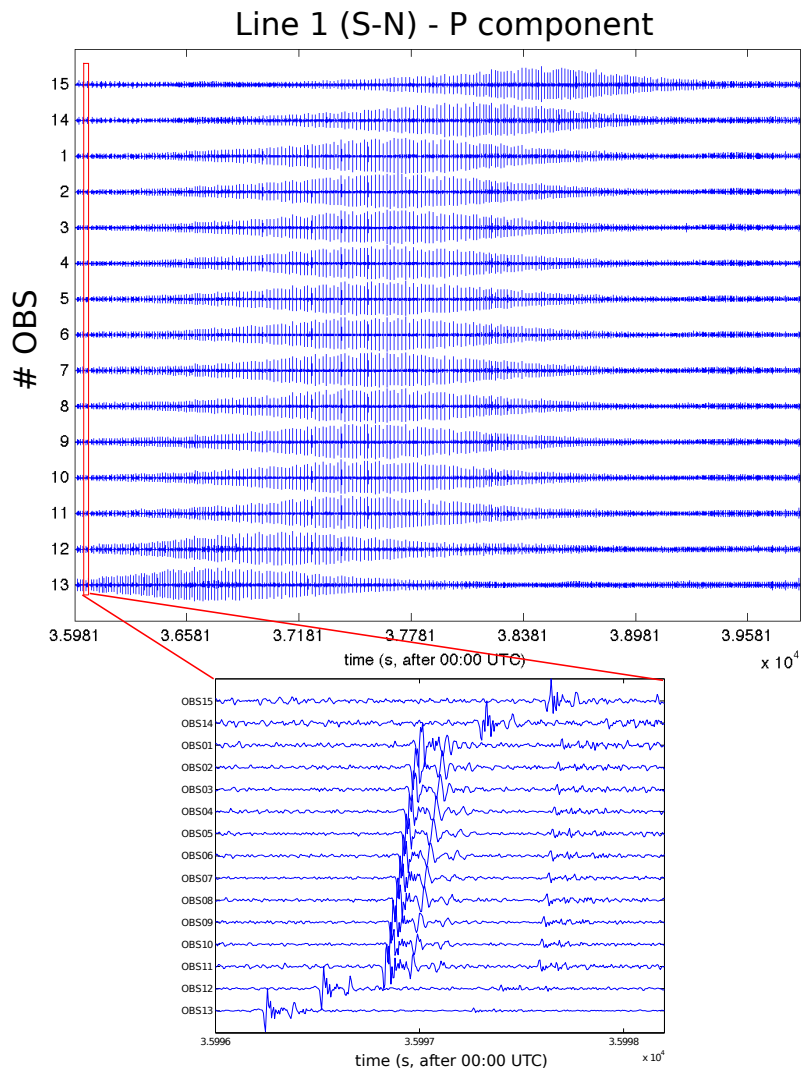


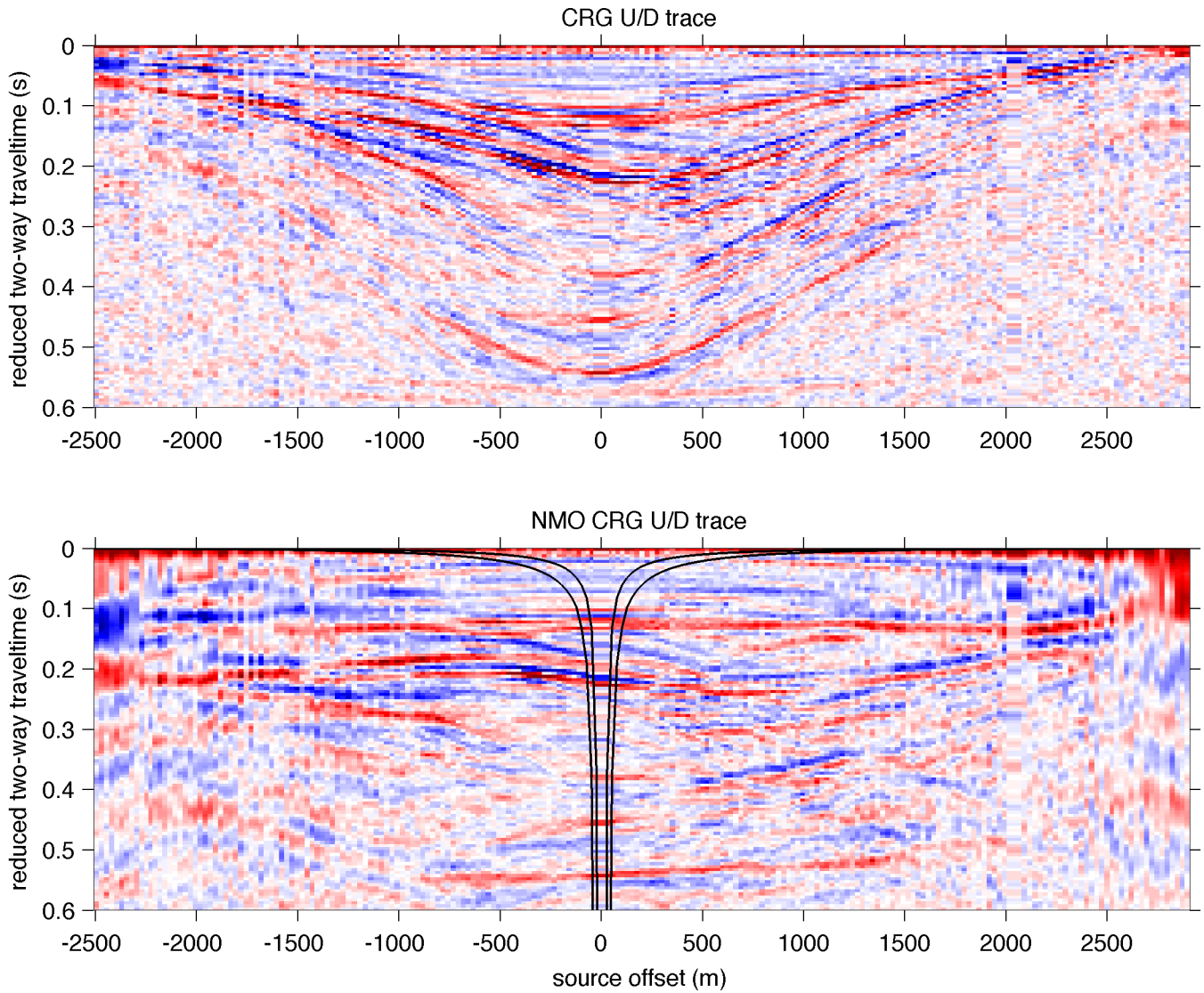
FIGURE 11.49. Velocity semblance plot. Velocity analysis of synthetic data corresponding to a model of the subsurface with one high-velocity basalt layer. The model is superimposed on the CMP gather. Note the significant misfit between theoretically computed rms velocities (black dots superimposed on a white curve) and the semblance peaks (red). This misfit results from the presence of the basalt layer. PP indicates P-to-P reflection, PS and P-S indicate P-to-S reflections.

Common receiver gather





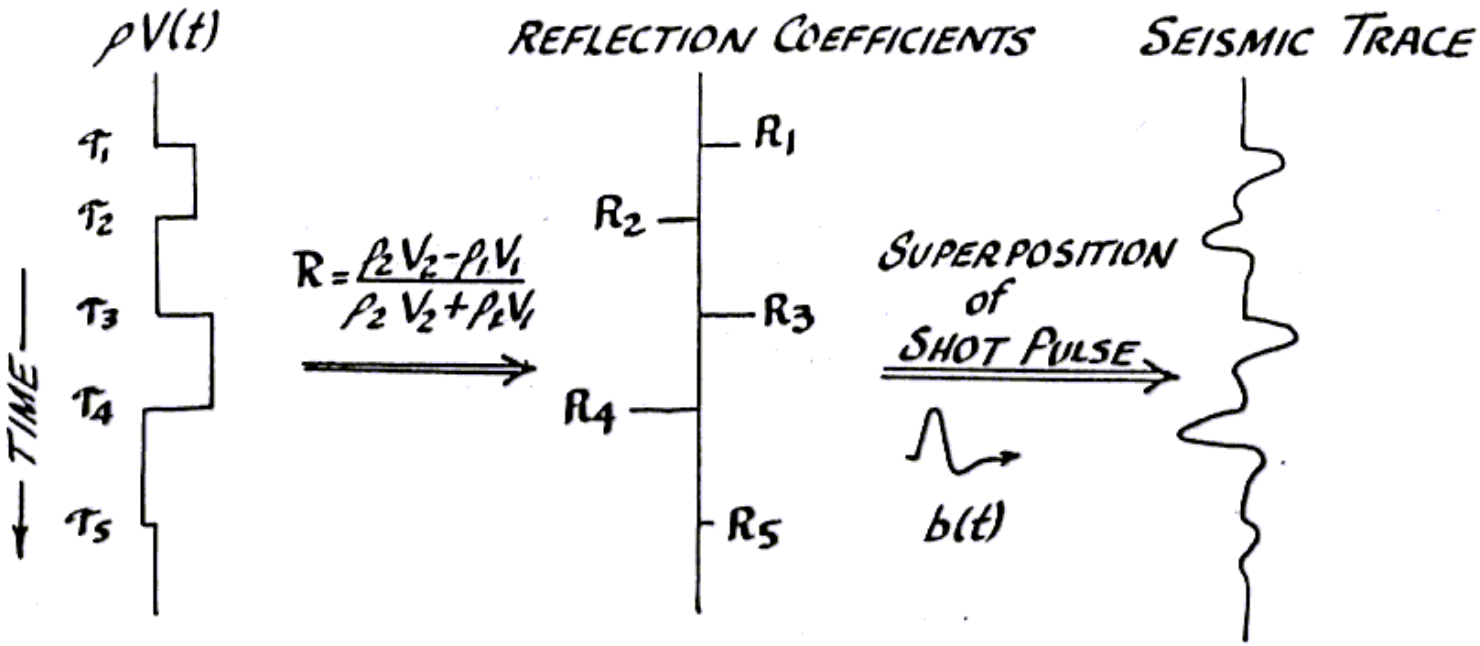
Common receiver gather and NMO



Reflection seismology – part 2

- Source, convolution and deconvolution
- Migration

Convolution



$$S(t) = R_1\, b(t-\tau_1) + R_2\, b(t-\tau_2) + R_3\, b(t-\tau_3) + R_4\, b(t-\tau_4) + R_5\, b(t-\tau_5)$$

SEISMIC TRACE = WEIGHTED and DELAYED SUPERPOSITION of SHOT PULSE.

$$S(t) = R(t) * b(t)$$

Convolution

The combination of the Earth response with the source-time function is termed *convolution* (see Appendix 5) and may be written as

$$u(t) = s(t) * G(t) \equiv \int_0^{t_s} s(\tau)G(t-\tau)\,d\tau, \tag{7.14}$$

In the frequency domain, the convolution becomes a product

$$u(\omega) = s(\omega)G(\omega), \tag{7.15}$$

Sources and deconvolution

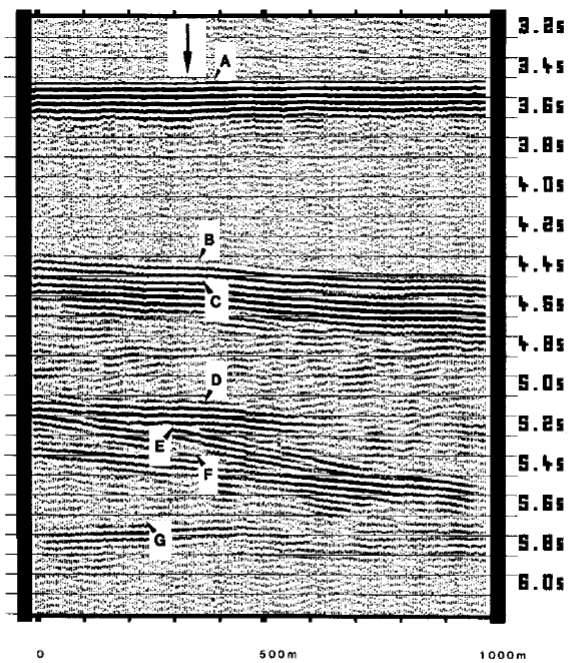
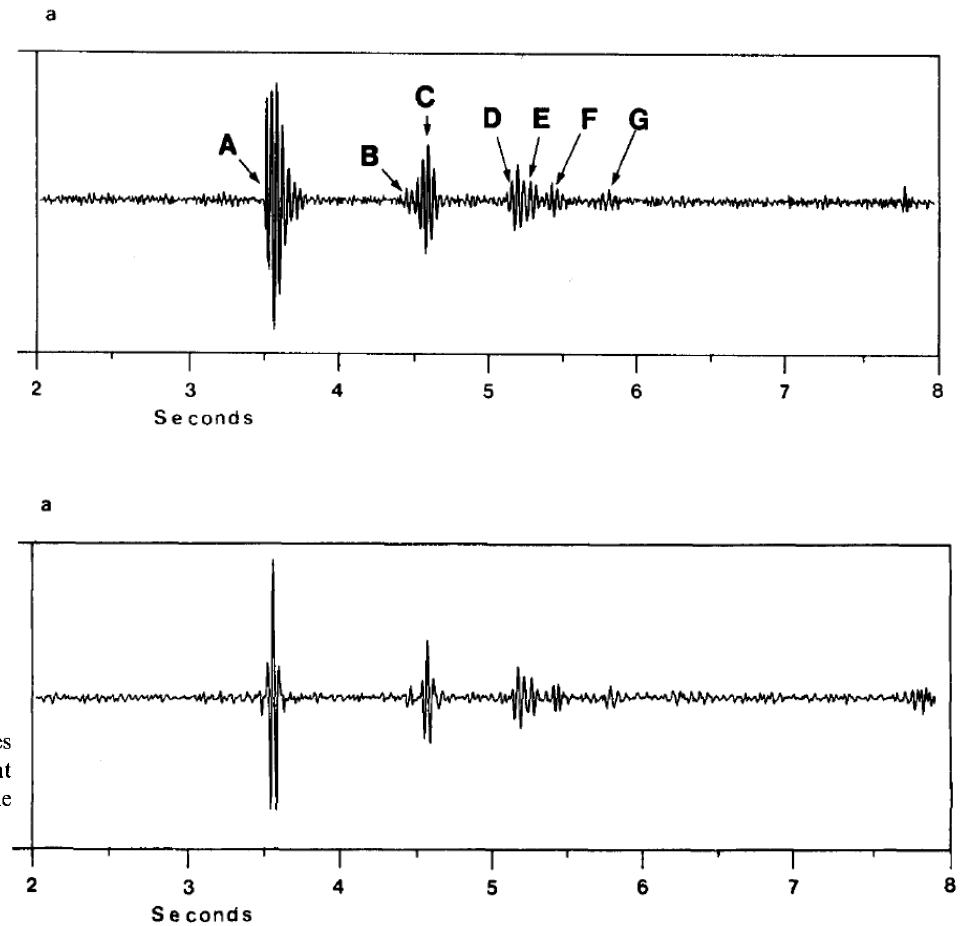


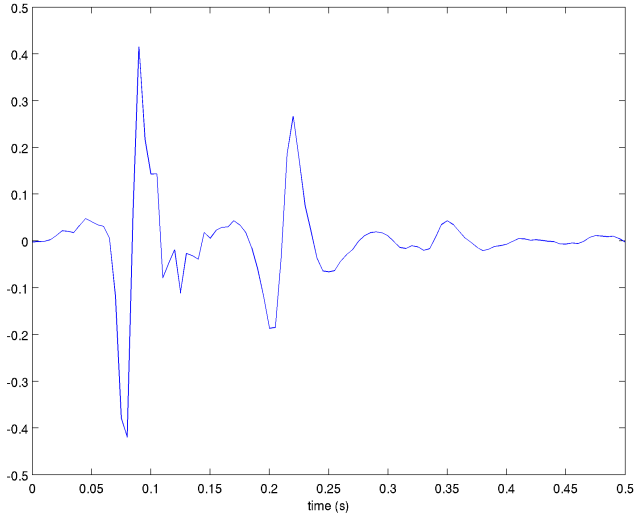
Fig. 2. Display of the section obtained with the near-bottom profiler (200 traces unprocessed). The first arrival (A) is the direct arrival from airguns to streamer, subsequent arrivals (B–G) are reflections. The vertical axis is two-way travel time. The arrow shows the point from which the single representative trace in fig. 3 is taken.



Sources

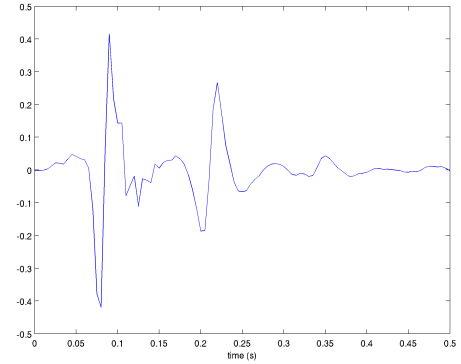
Air gun deployment in the Gulf of Mexico

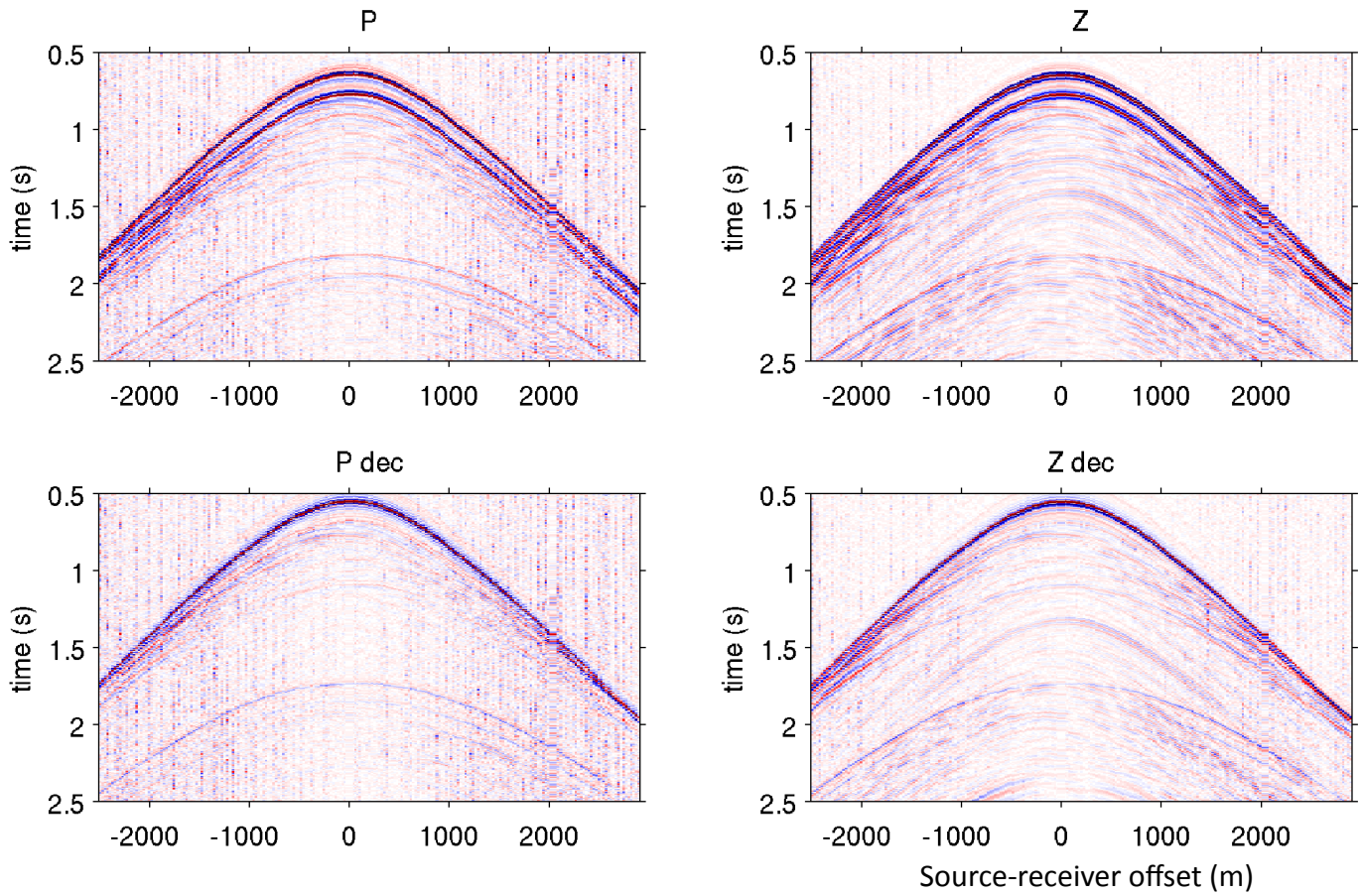
Air gun firing



Estimated source signal

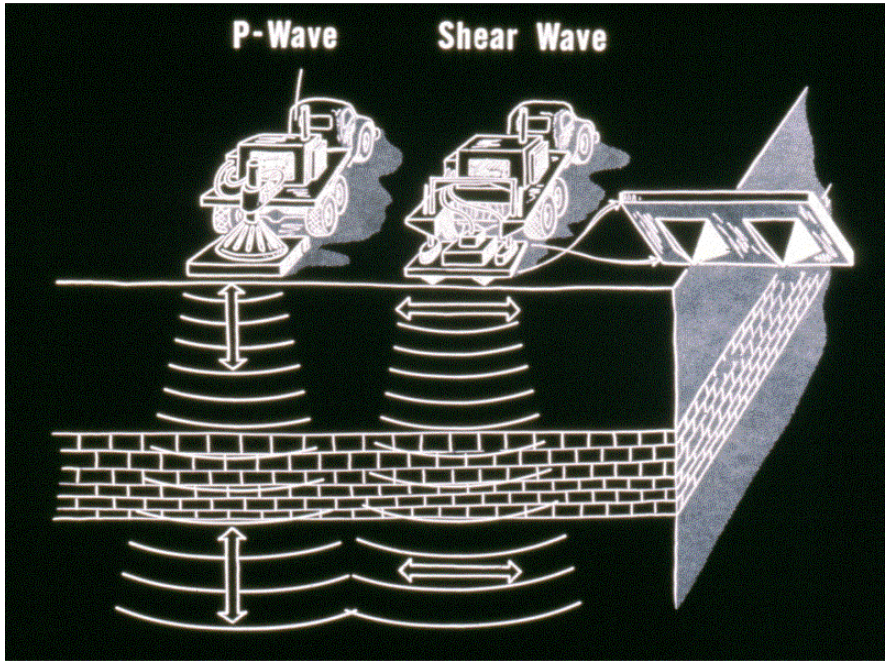
Sources and deconvolution





Vibroseis vibrators forming
a source array.

Schematic showing the forcing
functions of the P-wave
and S-wave Vibroseis seismic sources.



Divots left in the ground from the S-wave vibrator.

Sources and deconvolution

The cross-correlation $f(t)$ between two real functions $a(t)$ and $b(t)$ is defined as

$$f(t) = a(t) \star b(t) = \int_{-\infty}^{\infty} a(\tau - t) b(\tau)\, d\tau, \tag{7.18}$$

$$a(t) * b(t) = a(-t) \star b(t) \tag{7.19}$$

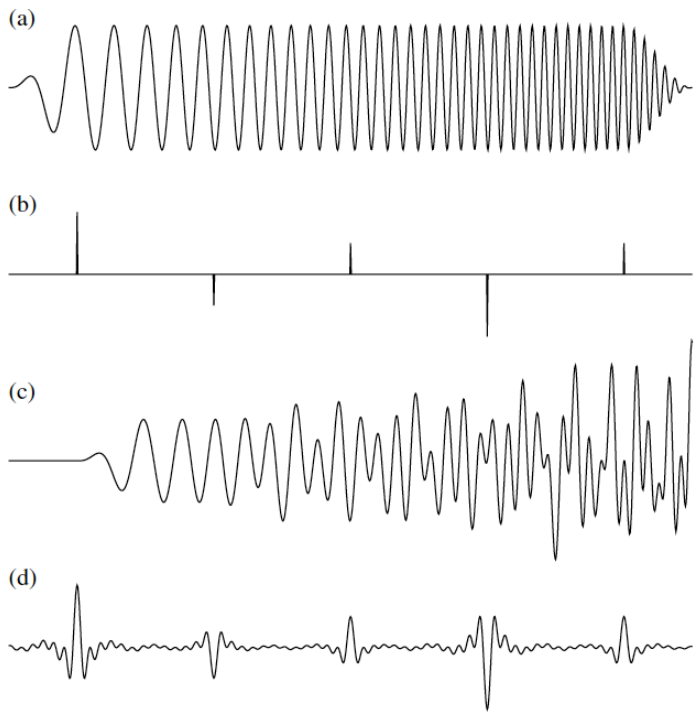


Figure 7.7: (a) An example of a vibroseis sweep function $v(t)$. (b) A hypothetical Earth response function $G(t)$. (c) The result of convolving (a) and (b). (d) The result of cross-correlating (a) with (c).

+ MATLAB

Resolution of structure

Consider a vertical step in an interface

To be detectable the step must cause an delay of ¼ to ½ a wavelength

This means the step (h) must be 1/8 to ¼ the wavelength (two way traveltime)

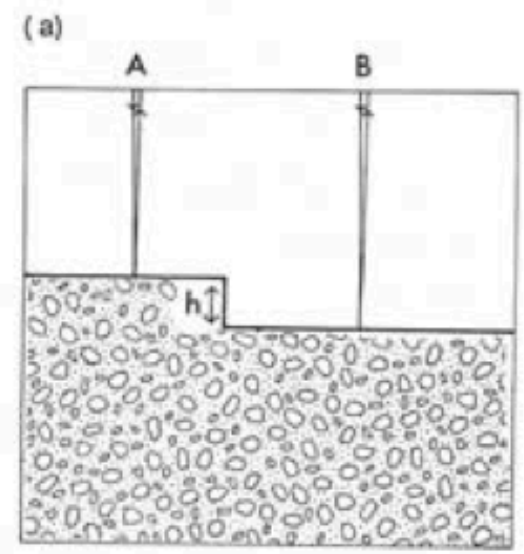
Example:

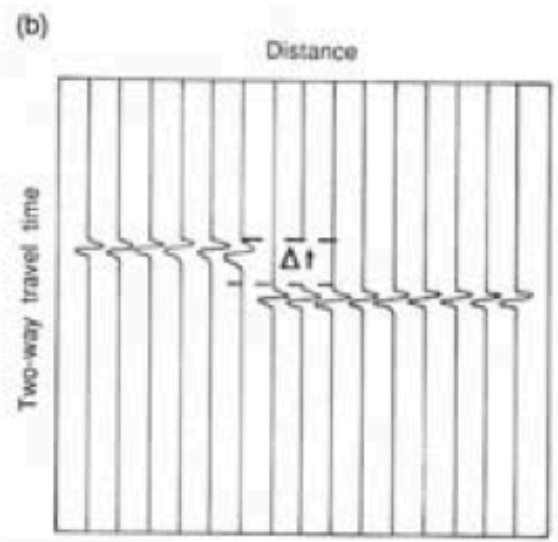
20 Hz, α = 4.8 km/s then λ = 240 m

Therefore need an offset greater than 30 m

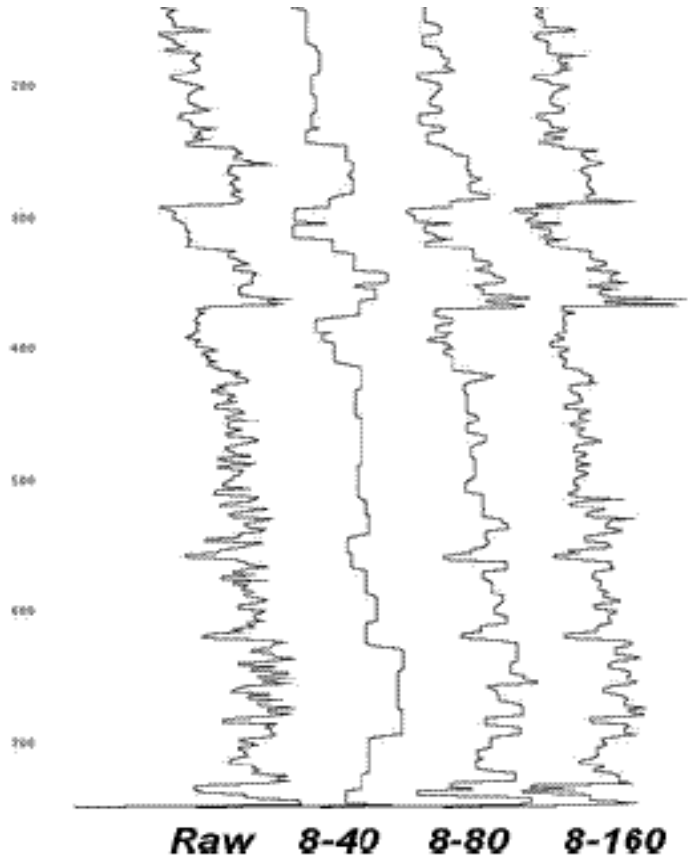
Shorter wavelength signal (higher frequencies) have better resolution.

What is the problem with very high frequency sources?





This illustrates what the acoustic impedance log might look like when inverted from seismic data of varying bandwidth.



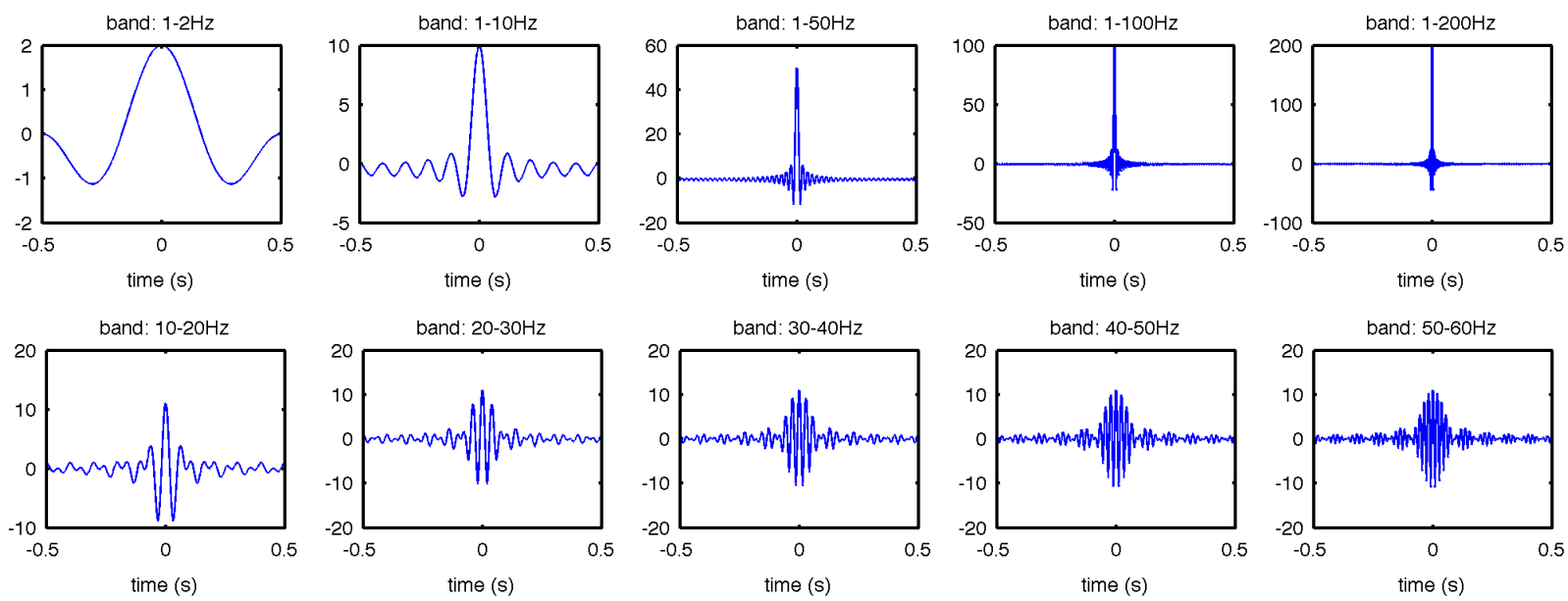
Data bandwidth tests. These diagrams show the detail that can be recovered with increasing seismic bandwidth. The left most log is the raw welllog impedance. Each of the 3 logs to its right were produced by running sparse spike inversion using a velocity model and seismic data of varying bandwidths. Numbers shown are frequencies in Hz.

With increasing depths, velocity tends to increase
frequency tends to decrease (attenuation)

→ Resolution gets worse with depth

V (m/sec)	f (Hz)	λ/4 (m)
2000	50	10
3000	40	18
4000	30	33
5000	20	62

Effect of bandwidth



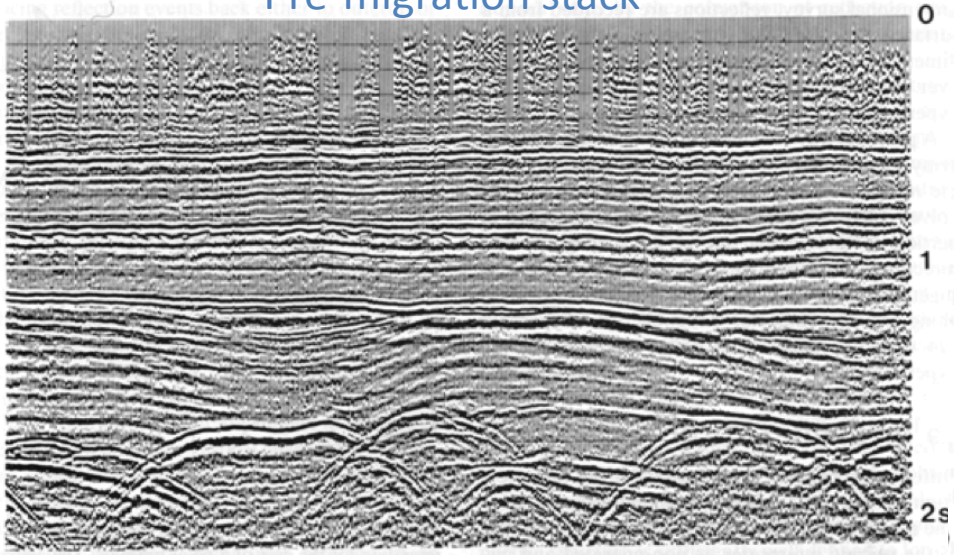
MIGRATION

Migration is an inversion operation involving rearrangement of seismic information elements so that reflections and diffractions are plotted at their true locations

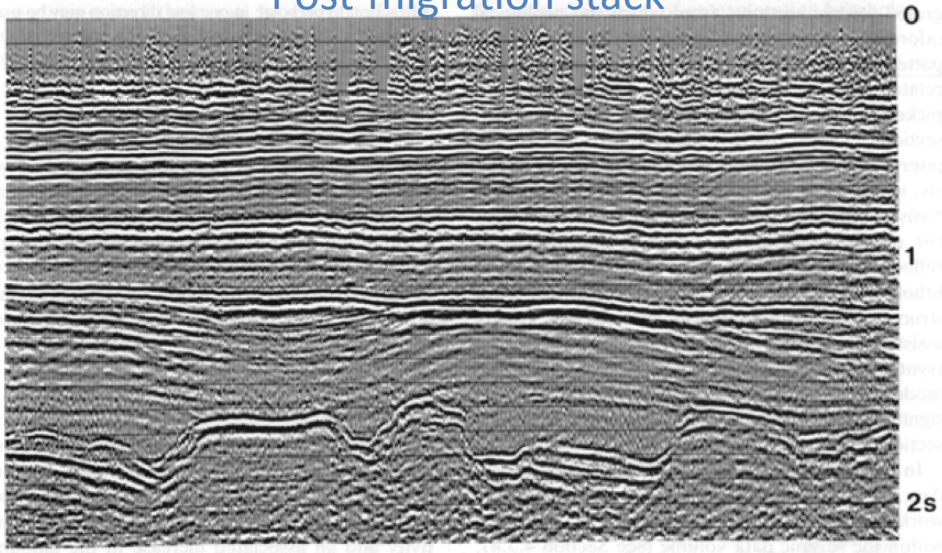
Simple structures (horizontal layers, CMP geometry, parallel dipping) : (modified) NMO

Complex structures (scattered and diffracted arrivals) : migration

Pre-migration stack

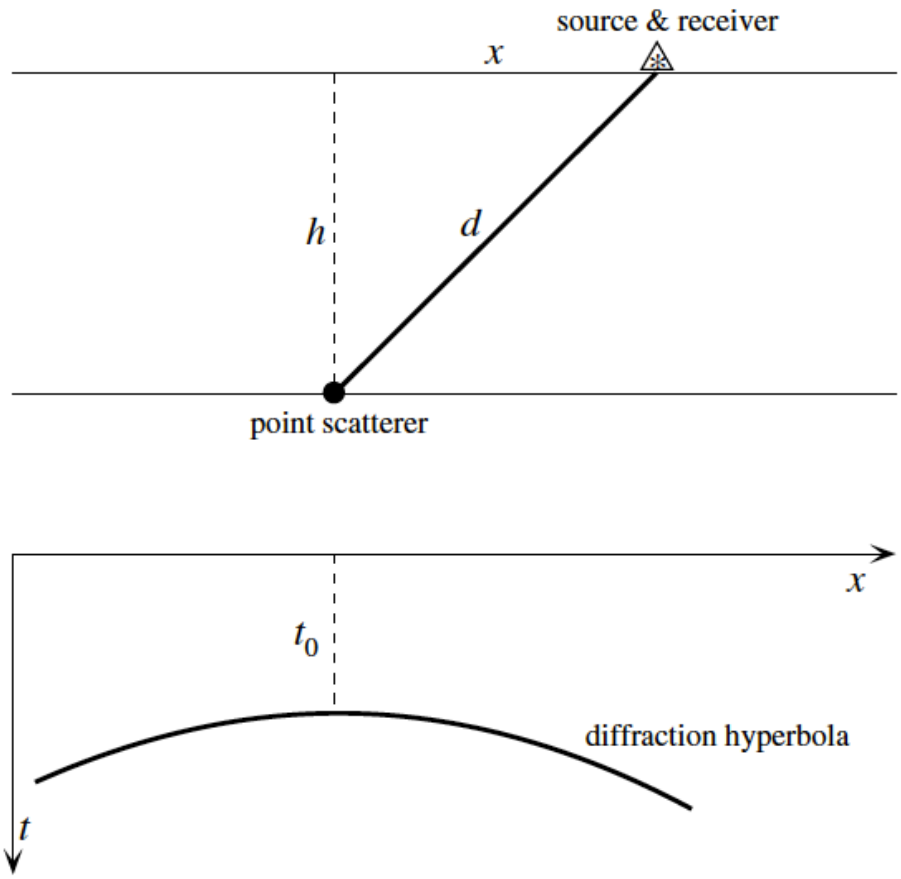


Post-migration stack



Migration: diffraction hyperbolas

Huygens' principle : each point on a reflector generates a secondary source in response to the incident wavefield



- Zero-offset section

- minimum travel time

$$t_0 = \frac{2h}{v},$$

- travel time as a function of horizontal distance between S,R and scatterer

$$t(x) = \frac{2\sqrt{x^2 + h^2}}{v}$$

- Travel time curve for the scattered arrival

$$\frac{t^2}{t_0^2} - \frac{4x^2}{v^2 t_0^2} = 1$$

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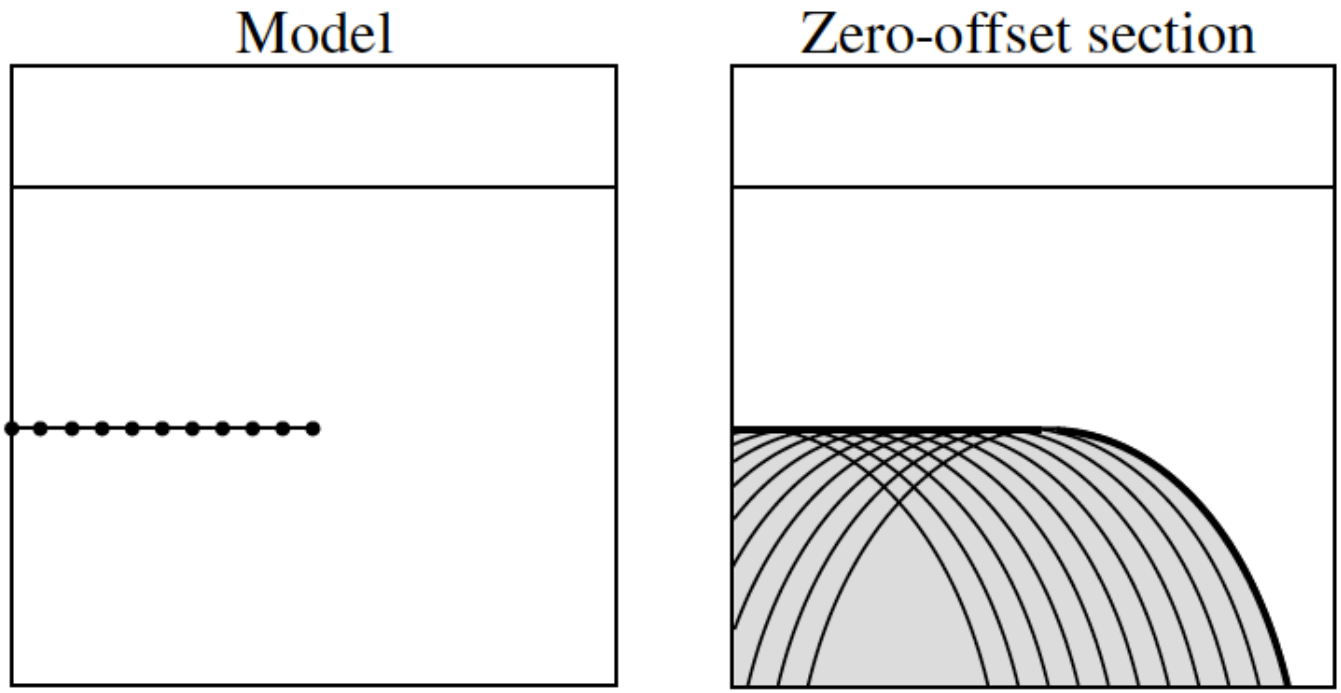


Figure 7.10: The endpoint of a horizontal reflector will produce a diffracted arrival in a zero-offset section. The reflector itself can be modeled as the coherent sum of the diffraction hyperbola from individual point scatterers. The diffracted phase, shown as the curved heavy line, occurs at the boundary of the region of scattered arrivals.

Diffraction summation migration

Each point is the apex of a hypothetical diffraction hyperbola

→ Average data from adjacent traces *along* the hyperbola

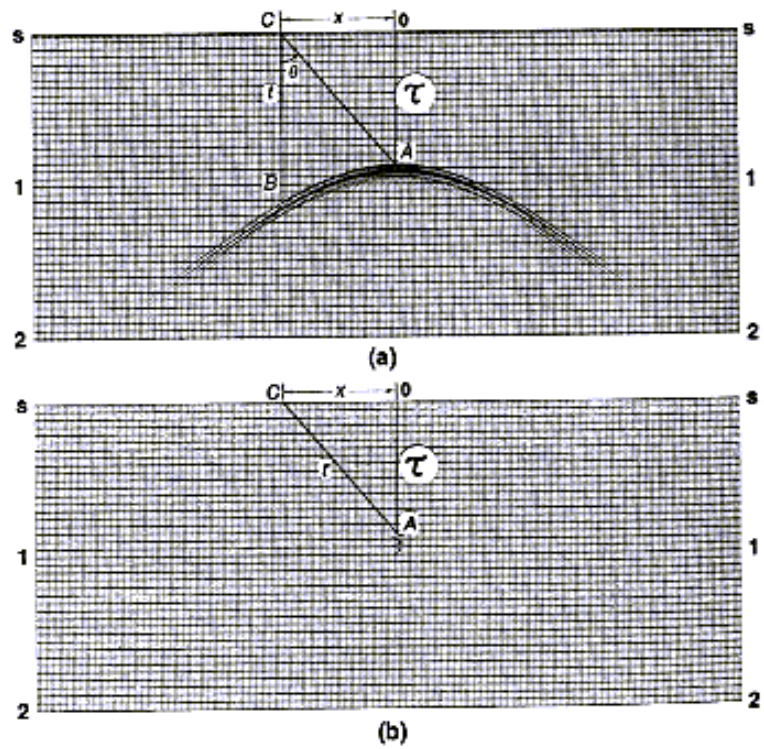
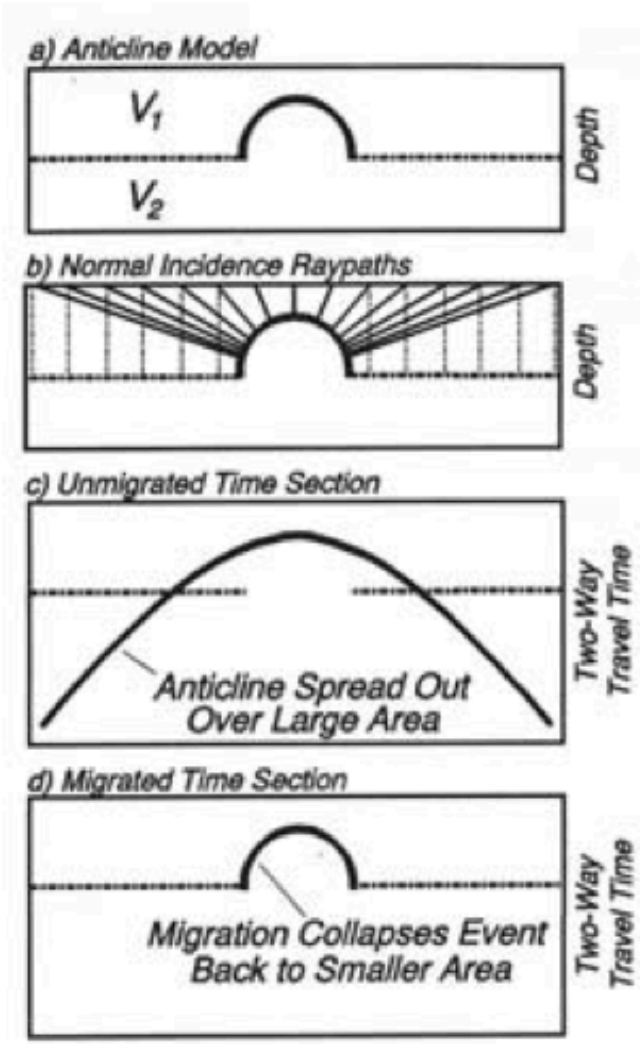
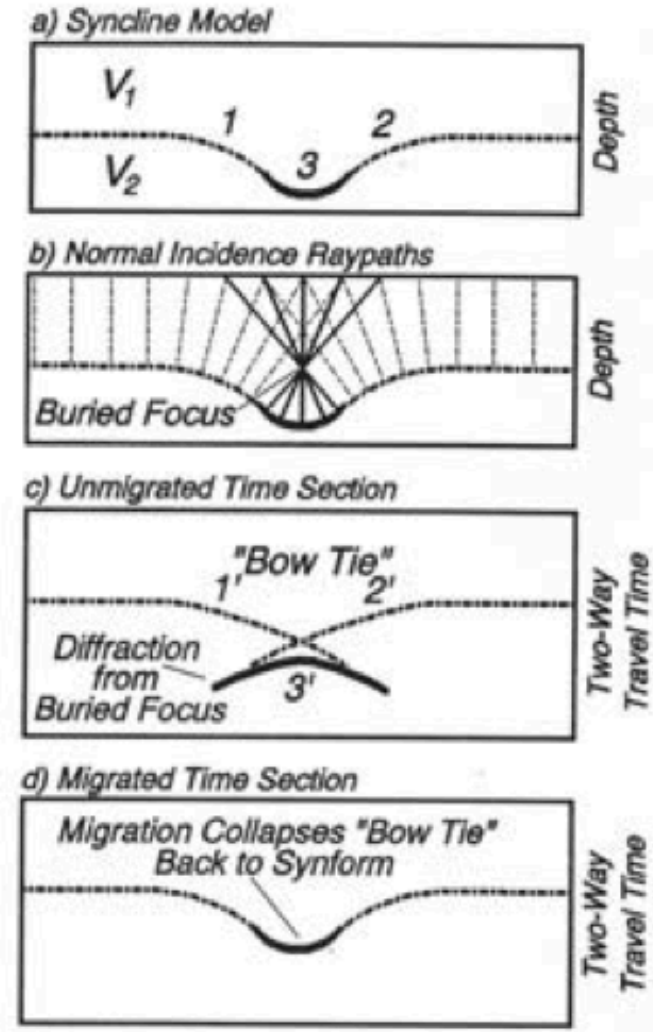


FIG. 4.1-15. Principles of migration based on diffraction summation. (a) Zero-offset section (trace interval, 25 m; constant velocity, 2500 m/s), (b) migration. The amplitude at input trace location B along the flank of the traveltime hyperbola is mapped onto output trace location A at the apex of the hyperbola by equation (4-4).

Anticlines and synclines





Anticlines broaden

Synclines produce a bow-tie

Proper implementation of diffraction summation migration

- the scattered amplitudes vary as a function of range and ray angle
- the Huygens secondary sources are given by the time derivative of the source-time function (3D) or, in frequency domain, a factor $-i\omega$
- in 2D the secondary sources are the "half-derivative" of the source function

→ Kirchoff theory

The diffraction hyperbola equation assumes a uniform velocity structure, but migration concepts can be generalized to more complicated velocity models. The use of the wrong model can result in "undermigrated" or "overmigrated" sections.

Data (→ Deconvolution) → CMP stacking → migration [*Poststack* migration]

Data (→ Deconvolution) → Migration → stacking [*Prestack* migration]
(superior results, greater computational cost)

Additional exercise

(a) You can build a wavelet by adding a cosine function at several frequencies, over the time interval [-0.5s,0.5s]. Tests 1-2Hz, 1-10Hz, 1-50Hz and 1-100 Hz (you can consider a frequency interval of 1Hz). Comment the differences.

(b) Build 10-Hz bandwidth wavelets with central frequency of 20Hz, 50 Hz and 100 Hz. Comment the differences.

(c) Consider two reflection events separated by 50ms (two-way traveltime). What is the minimum frequency to transmit to resolve these two events (consider a velocity of 2000 m/s).
Test the wavelets you have build in point (a) and (b). (note: convolve with a time series with 0 everywhere except at two points separated by 50 ms). What is your conclusion ?