The SEISMIC method
for geothermal exploration

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These methods can be divided into two main subclasses:

active seismic methods, which cover all seismic prospecting having an artificial sonic wave source;

passive seismic methods, which deal with the effects of natural earthquakes or those induced by fracturing related to geothermal fluid extraction and injection.

Seismic methods determine subsurface elastic properties influencing the propagation velocity of elastic waves and can be very helpful in obtaining structural information of the subsurface or even to outline a potential reservoir.

Waves

Elastic waves are generated whenever there is

- A sudden deformation
- A sudden movement of the portion of a medium

Waves

Examples of man-made seismic sources:

- Explosion
- Weight drop
- Drilling
- Vibroseis (tractions), ...

Elastic waves

When a stress is applied (or released) the corresponding strain propagates out from the source.

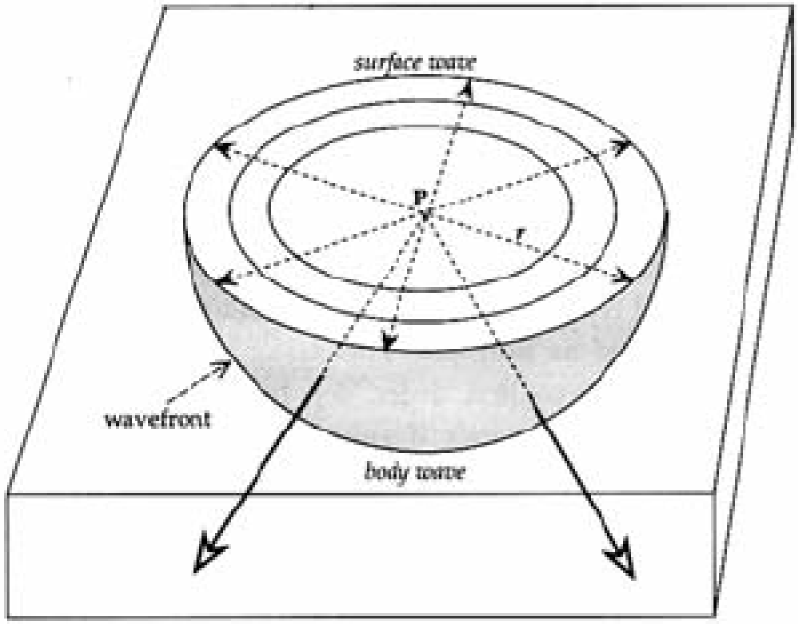
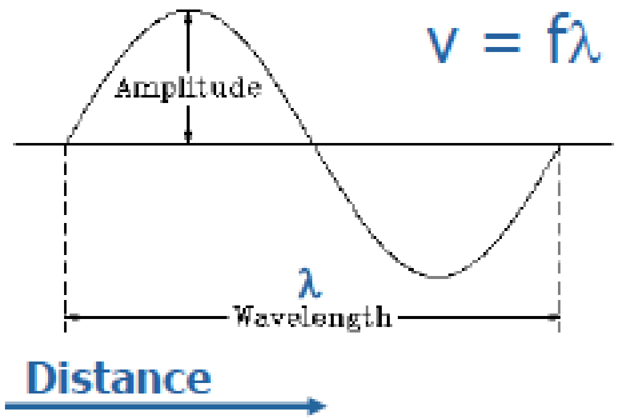


Fig. 3.9 Propagation of a seismic disturbance from a point source P near the surface of a homogeneous medium; the disturbance travels as a body wave through the medium and as a surface wave along the free surface.

Point source seismic disturbance:

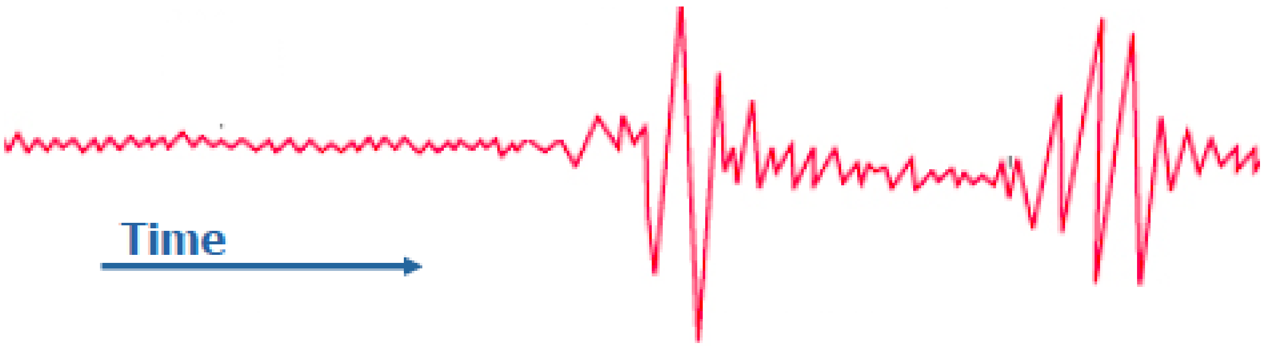
- Wavefront expands out from the point: **Huygen's Principle**
- Body waves: sphere
- Surface waves: circle
- **Rays**: perpendicular to wavefront

Waves – a reminder

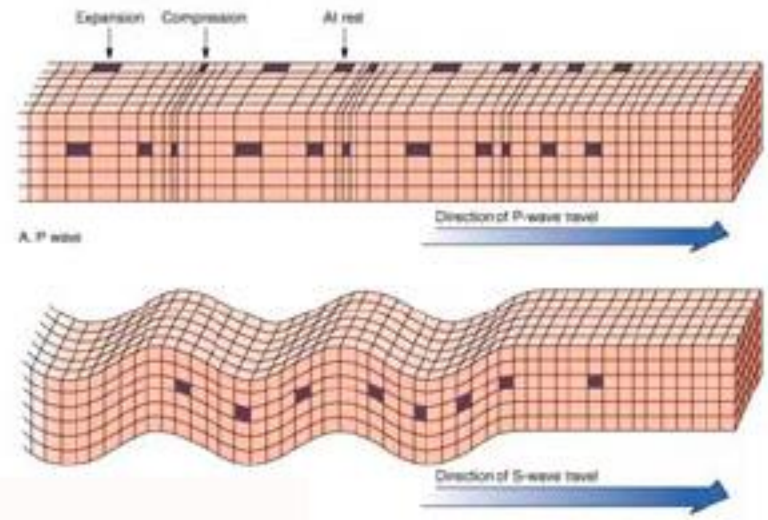


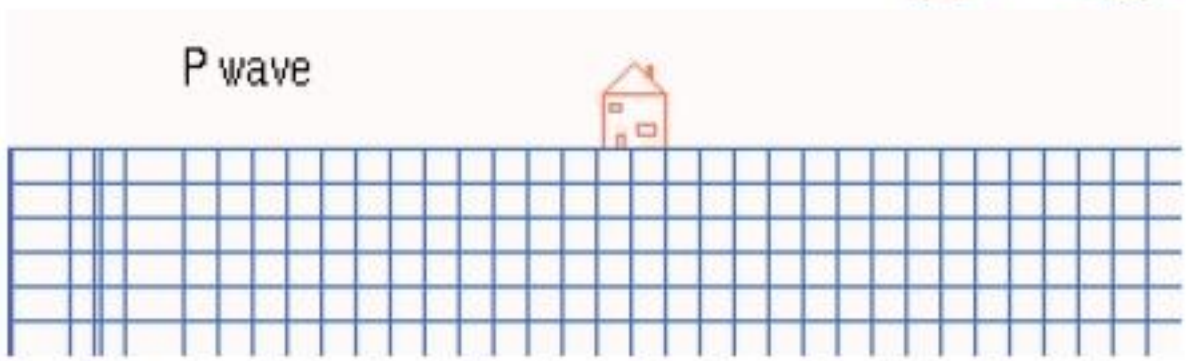
$v = f\lambda$

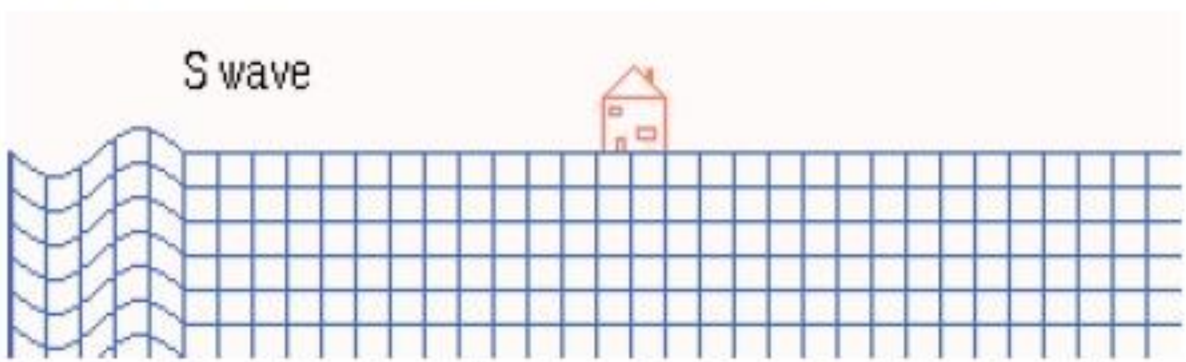
- Velocity, v
- Wavelength, λ
- Frequency, f
- Period, $T = 1/f$



Body waves
P and S-waves







P and S-velocities

P-velocity

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

change of shape and volume

S-velocity

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

change of shape only

For liquids and gases $\mu = 0$, therefore

➔ $V_S = 0$ and V_P is reduced in liquids and gases

➔ Highly fractured or porous rocks have significantly reduced V_P

The bulk modulus, κ is always positive, therefore $V_S < V_P$ always

P-waves are the most important for controlled source seismology

- They arrive first making them easier to observe
- It is difficult to create a shear source, explosions are compressional

Factors affecting velocity

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

Density – velocity typically increases with density

(κ and μ are dependant on ρ and increase more rapidly than ρ)

Porosity and **fluid saturation**

Increasing porosity reduces velocity.

Filling the porosity with fluid increases the velocity.

$$\frac{1}{V_{sat}} = \frac{\phi}{V_F} + \frac{1-\phi}{V_M}$$

Poisson's ratio – related to V_P/V_S

This is used to distinguish between rock/sediment types. It is usually more sensitive than just V_P alone.

The significant variations in sediments are usually due to porosity variations and water saturation. Water saturation has no effect on V_S (for low porosities) but a significant effect on V_P.

Parameters affecting velocity

$$V_p = \sqrt{\frac{K+4/3\mu}{\rho}}$$

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

Depth

Lithology

Porosity

Density (ρ)
Compressibility (1/k)
Rigidity (μ)

Pressure

Anisotropy

Temperature

Compaction

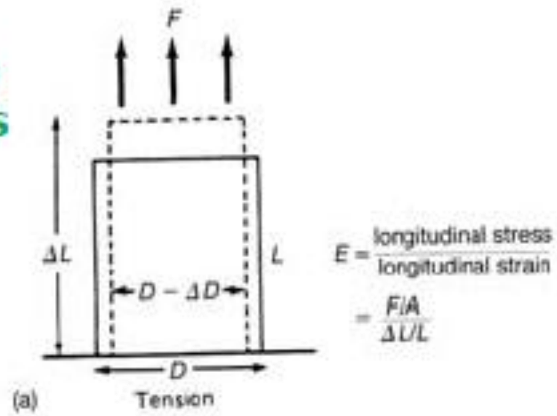
Cement

Pore fluid

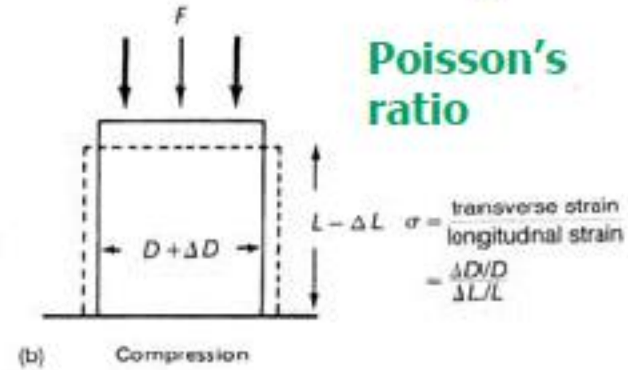
Elastic moduli

describe the physical properties of the rock ...and determine the seismic velocity

Young's modulus

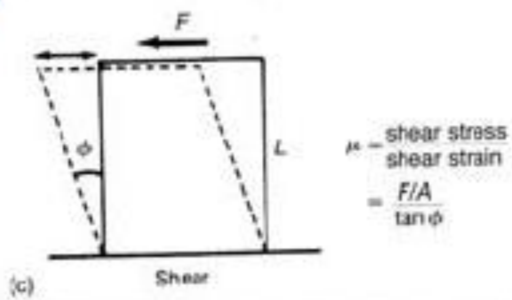


Poisson's ratio



Shear modulus, μ

- Force per unit area to change the shape of the material



Bulk modulus, κ

- Ratio of increase in pressure to associated volume change
- Always positive

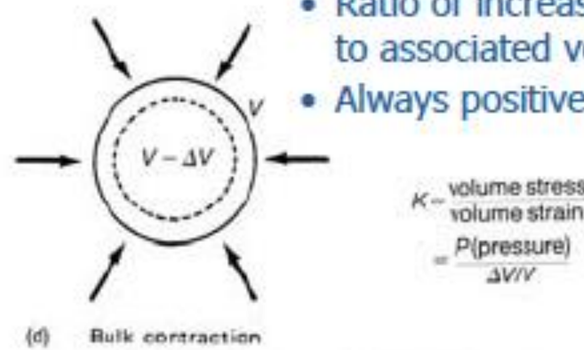
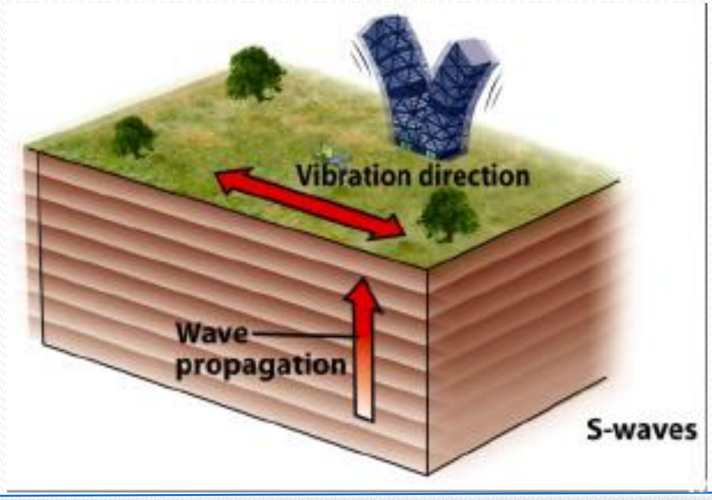


Fig. 4.2 Common types of elastic stress and strain. Cross-sections of bodies shown before strain (solid line) and after strain (dashed line). Directions of stress are shown by thick arrows. The related elastic moduli are defined (a,b) Young's modulus, E, and Poisson's ratio, σ; (c) shear (or rigidity) modulus, μ; (d) bulk modulus, K: application of uniform pressure shown by thick arrows around the body. Poisson's ratio is a measure of the relative deformation of the body in two perpendicular directions. F denotes the force acting on a cross-sectional area A.

Two types of deformation

Source Duan 2010)

Volumetric change (P-waves, compressional waves)

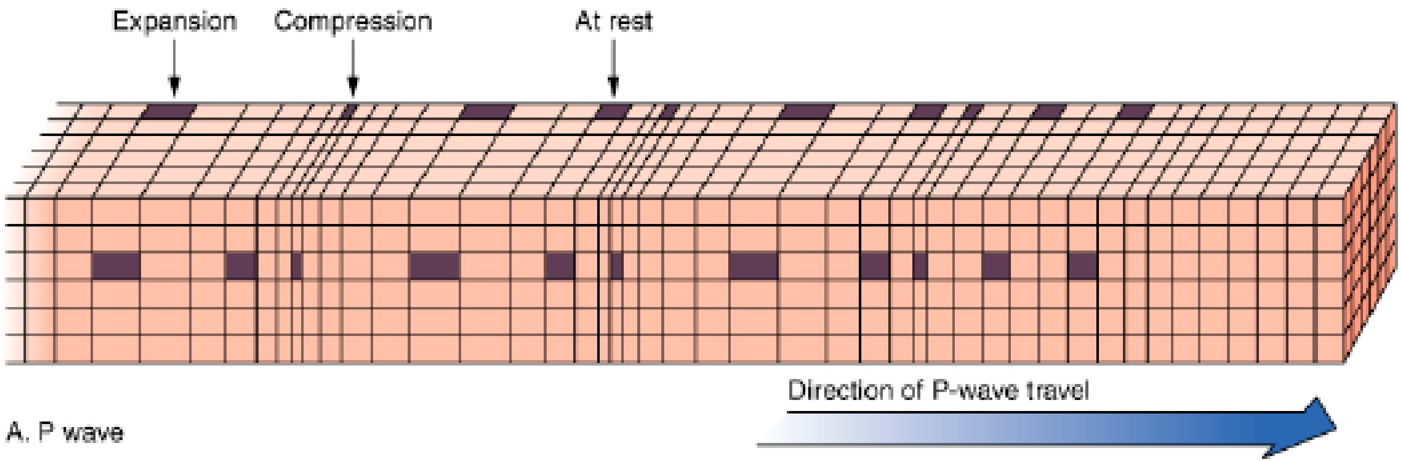


Change of shape (S-waves, shear waves)

Body waves
P-waves

- P for "primary" or "push-pull"
- Compression and rarefaction, no rotation
- Causes volume change as the wave propagates
- Similar to sound waves traveling through air

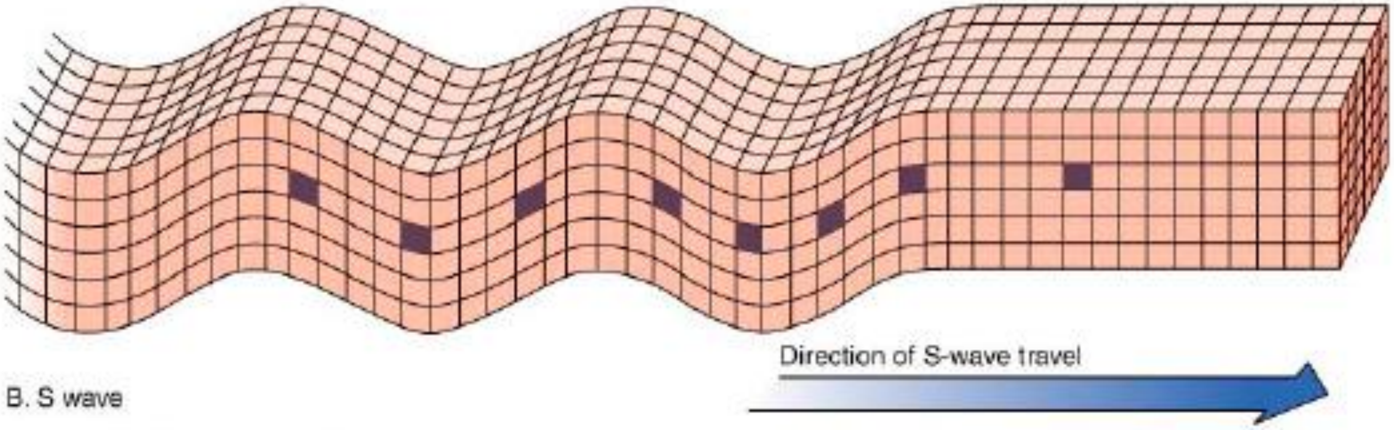
- The fastes wave
- Travel through solid, liquid and gas

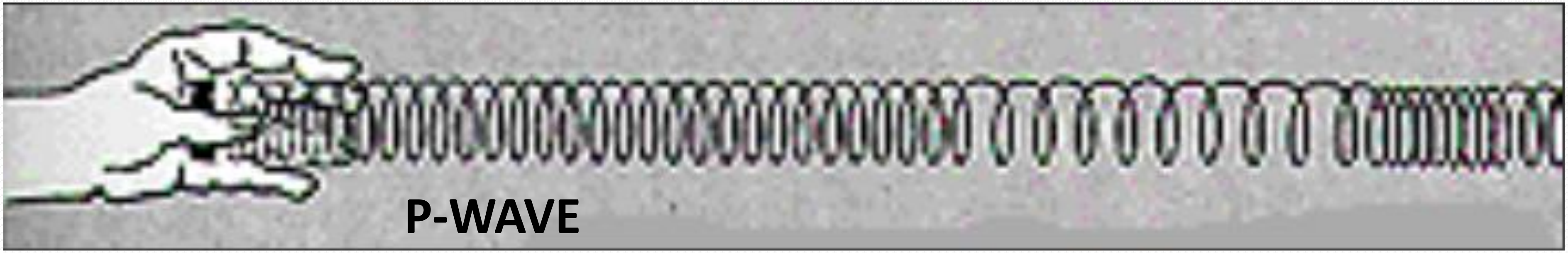


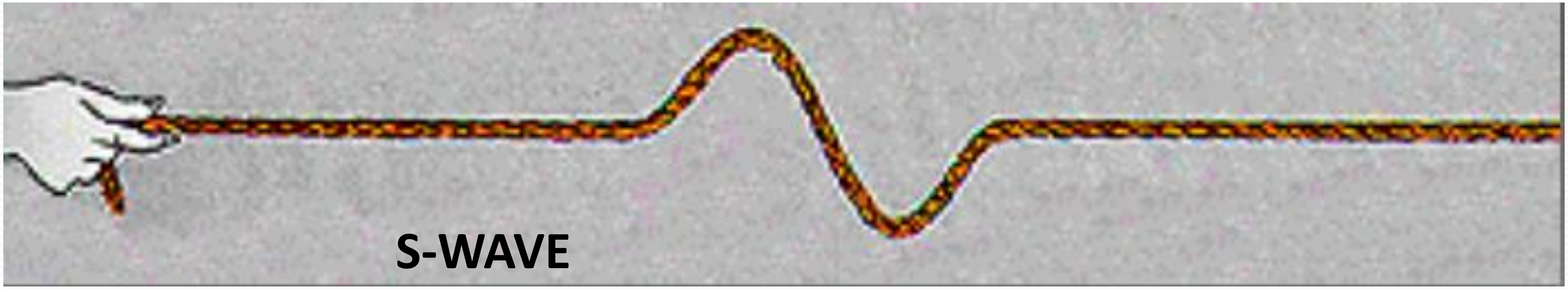
Body waves
S-waves

- S for "secondary" or "shear" and "shake"
- Shearing and rotation
- No volume change as the wave propagates

- **Right angle to direction of wave**
- **About half the speed of P-waves**
- **Travel only through solid**




P-WAVE


S-WAVE

Typical rock velocity ranges

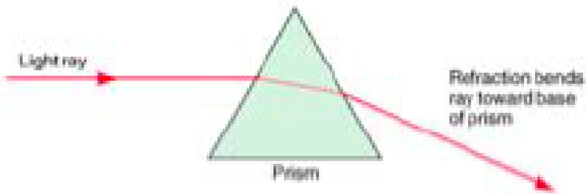
Table 4.1 *Compressional wave velocities (V_p) in rocks.*

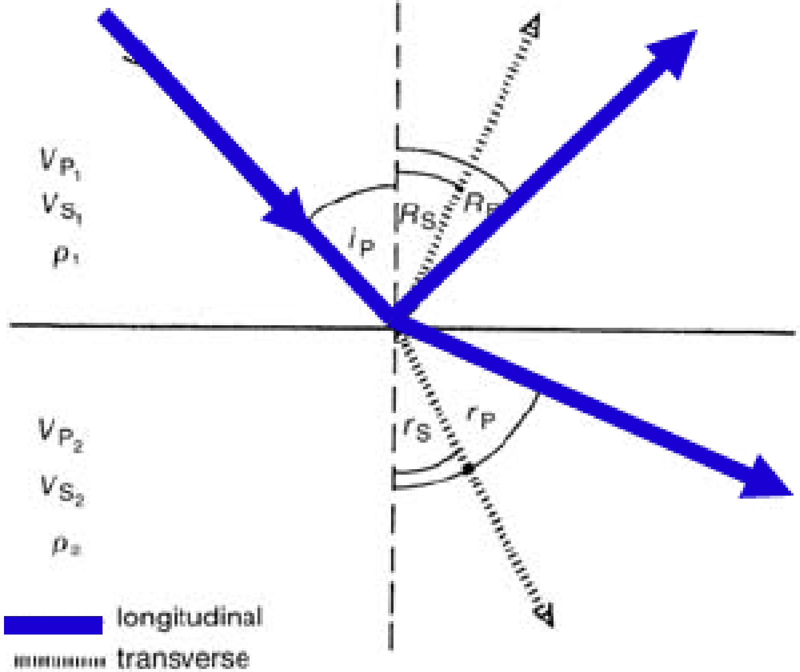
Rock type	V_p(m/s)
Air	330
Water	1400–1500
Ice	3000–4000
Permafrost	3500–4000
Weathered layer	250–1000
Alluvium, sand (dry)	300–1000
Sand (water-saturated)	1200–1900
Clay	1100–2500
Glacial moraine	1500–2600
Coal	1400–1600
Sandstones	2000–4500
Slates and shales	2400–5000
Limestones and dolomites	3400–6000
Anhydrite	4500–5800
Rocksalt	4000–5500
Granites and gneisses	5000–6200
Basalt flow top (highly fractured)	2500–3800
Basalt	5500–6300
Gabbro	6400–6800
Dunite	7500–8400

Note:
For a more extensive compilation of compressional and shear wave velocity data the reader may refer to Bonner and Schock (1981).

Using velocity alone to determine rock type is problematic to impossible.

Reflection and transmission





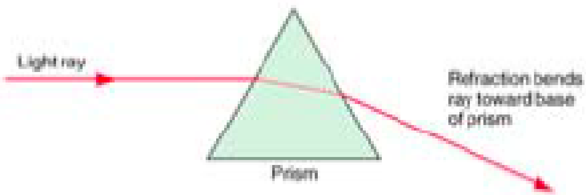
Seismic rays obey Snell's Law

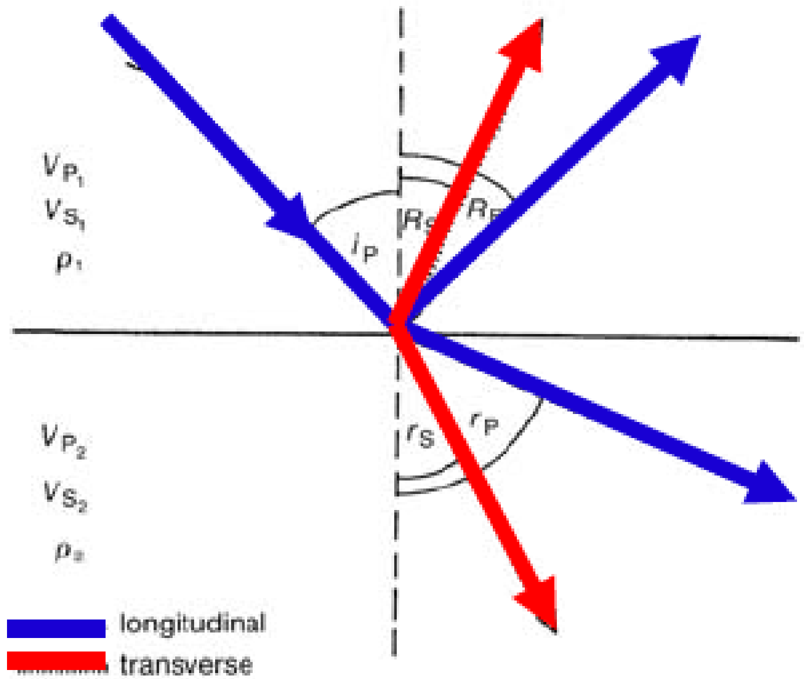
(just like in optics)

The angle of incidence equals the angle of reflection, and the angle of transmission is related to the angle of incidence through the velocity ratio.

$$\frac{\sin i_P}{V_{P1}} = \frac{\sin R_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}}$$

Reflection and transmission





Seismic rays obey Snell's Law

(just like in optics)

The angle of incidence equals the angle of reflection, and the angle of transmission is related to the angle of incidence through the velocity ratio.

But a conversion from P to S or vice versa can also occur. Still, the angles are determined by the velocity ratios.

$$\frac{\sin i_P}{V_{P1}} = \frac{\sin R_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}} = \frac{\sin R_S}{V_{S1}} = \frac{\sin r_S}{V_{S2}} = p$$

where p is the **ray parameter** and is constant along each ray.

Amplitudes reflected and transmitted

The amplitude of the reflected, transmitted and converted phases can be calculated as a function of the incidence angle using **Zoeppritz's equations**.

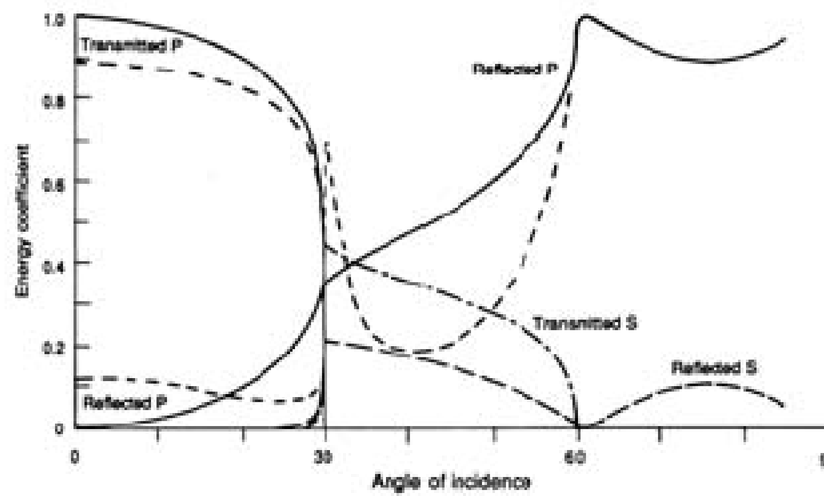
Simple case: **Normal incidence**

Reflection coefficient

$$R_C = \frac{A_R}{A_i} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

Transmission coefficient

$$T_C = \frac{A_T}{A_i} = 1 - R_C = \frac{2\rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$



Reflection and transmission coefficients for a specific impedance contrast

These coefficients are determined by from the product of velocity and density – the **impedance** of the material.

R_C usually small – typically 1% of energy is reflected.

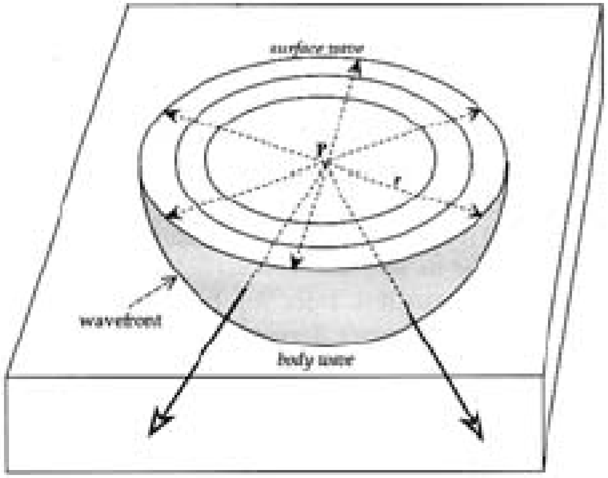
Attenuation

The amplitude of an arrival decreases with distance from the source

1. Geometric spreading

Energy spread over a sphere: $4\mu r^2$

Amplitude $\propto 1/r$



2. Intrinsic attenuation

Rocks are not perfectly elastic.

Some energy is lost as heat due to frictional dissipation.

Amplitude $\propto e^{-\alpha r}$

where α is the absorption coefficient (dependent on wavelength)

Total attenuation

$$A = (A_0\, e^{-\alpha r})/r$$

Higher frequencies attenuate over shorter distances due to their shorter wavelengths.

Therefore, high frequencies decay first leaving a low frequency signal remaining.

PASSIVE SEISMIC METHODS

The study of earthquakes and microearthqaukes naturally occurring, or occurring for independent reasons (not generated on purpose for the specific exploration)

Geothermal areas are often characterized by microseismic activity, although there is not a a one-to-one relationship.

Microseismic activity characterises modern tectonic activity, controlled by the same factors that control the emplacement of a geothermal system

Studies of micro earthquakes (MEQ) can serve as a guide when drilling into fractured rocks in a geothermal reservoir whose production levels are expected to be high.

6 to 12 or more highly sensitive seismograph units at a relative distance of no more than 5 – 10 km define the network.

Duration of prospection should be long enough to record a large number of events.

The rate of event depends on the magnitude (Richter *M* factor, which is a logarithmic scale indicating the amplitudes of seismic waves).

Usually, an inverse linear relationship between the logarithm of the number of earthquakes and their magnitudes has been observed.

If events of magnitude – 1 or – 2 can be recognised by seismometers, in a period of 30 to 60 days and in an area of seismic activity one would reasonably expect to record hundreds of events

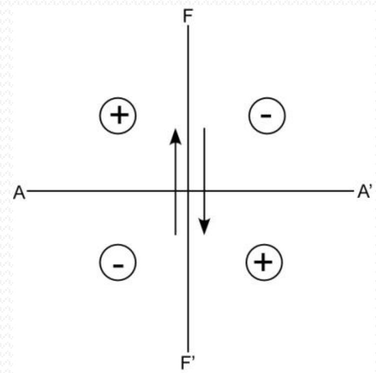
In defining hypocenters from arrival times of at several stations in an array, it is usually assumed that the earthquake energy was released from a *point source*, and that the seismic waves travelled through a *uniform earth* to be recorded at each seismometer

Seismic surveys of microseismicity require a sufficiently dense network of recording stations placed around the potential reservoir and an extended period of recording time, usually several months.

Several well-located events are necessary to reliably characterise an active fault. If these active faults are located, sophisticated use of recording and the recorded data can help to construct a three-dimensional image of fluid flow in the reservoir, as fluid circulation occurs in open faults and fracture systems, which are often responsible for the observed microseismicity.

The frequencies associated with fluid circulation in open fractures are usually at the lower limit of the recording spectrum. This problem can be solved by the use of broadband stations that record a much broader spectrum of frequencies than standard seismometers.

The first target of passive seismic method is to determine hypocenters, whose location is directly linked to those of faults – including those created by stimulation and hydrofracturing - and to the tectonic signature of the area. In addition, information about the geology and tectonics can be obtained from fault plane solutions and first motion studies of these earthquakes, which are valuable in determining whether the earthquake activity in a prospect area is anomalous or typical of the region.



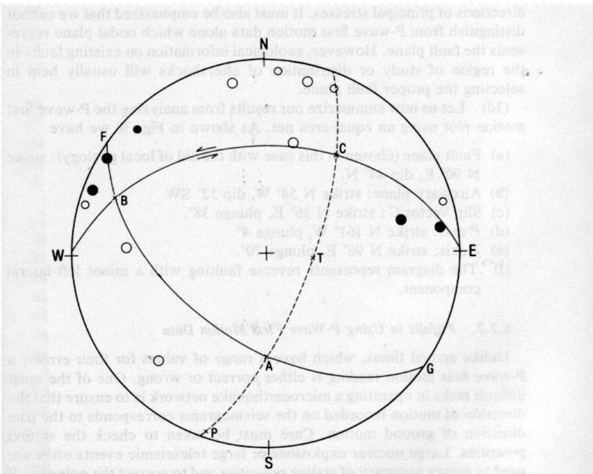


Fig. 30. A fault plane solution for a microearthquake in the Santa Barbara, California, region. The diagram is an equal-area projection of the lower focal hemisphere. See text for explanation.

Unknowns:
- *x, y,* and *z* coordinates of the origin
- the time at which the event occurred
- the subsurface wave speed distribution.

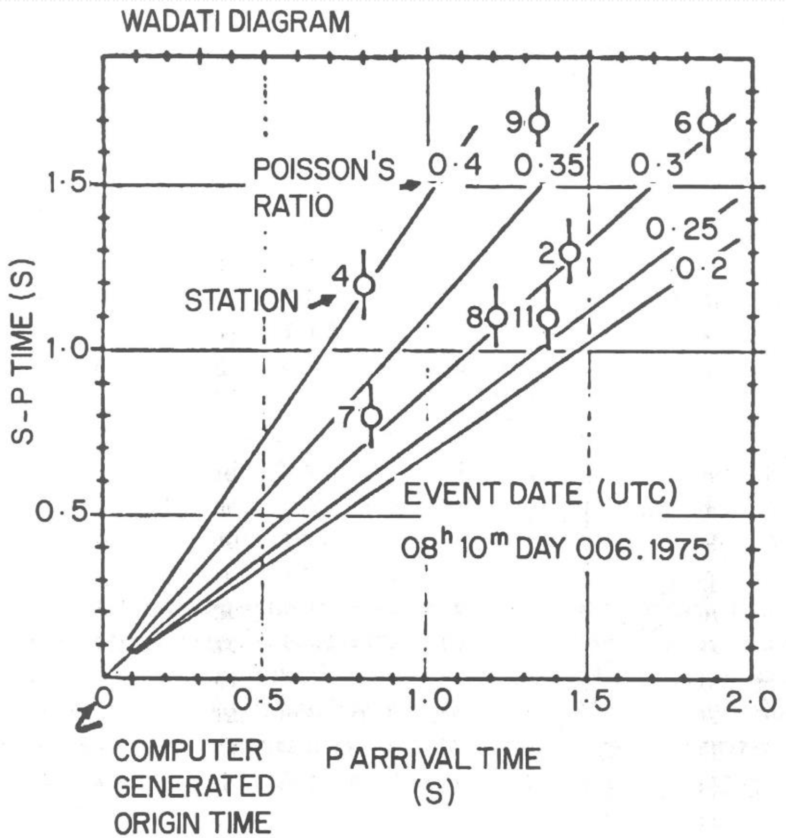
Assuming a constant wave speed (straight line travel from the origin to each receiver), 4 p-wave arrival times are enough to define the hypocenters

If s-wave arrival times as well as p-wave arrival times are available, 3 stations are enough and the solution is more stable.

Let’s see an old method, which has been replaced by more refined and modern technques, but explains well the basic concept of the analysis.

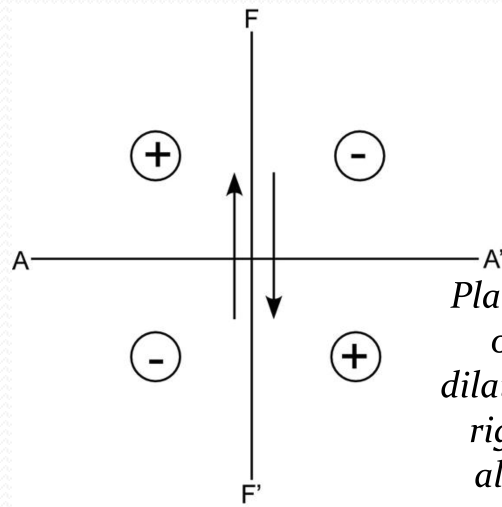
The Wadati diagram is a cross-plot between the p arrival times and the s – p arrival-time differences). Extrapolation of p versus p – s times to zero p – s difference gives the origin time for the earthquake.

Once an origin time is known, only three arrival times are needed to obtain a solution for the coordinates of an earthquake.

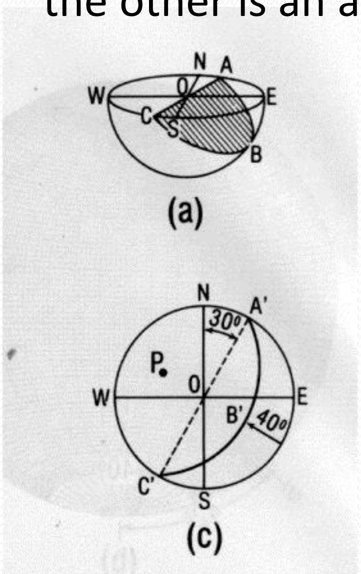


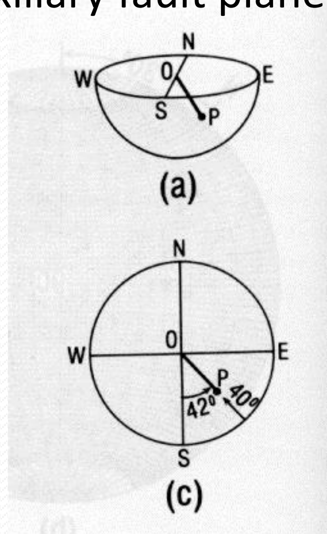
Fault plane solutions and first motion studies provide further information about the geology and tectonics of the area.

These are usually visualized by stereographic projection centred on the epicentre.
compressional first arrivals are denoted by solid circles and dilations by open circles
One of these planes is the fault plane itself, and the other is an auxiliary fault plane



Plan view of the distribution of compression (+) and dilatation (-) resulting from a right lateral displacement along a vertical fault FF')





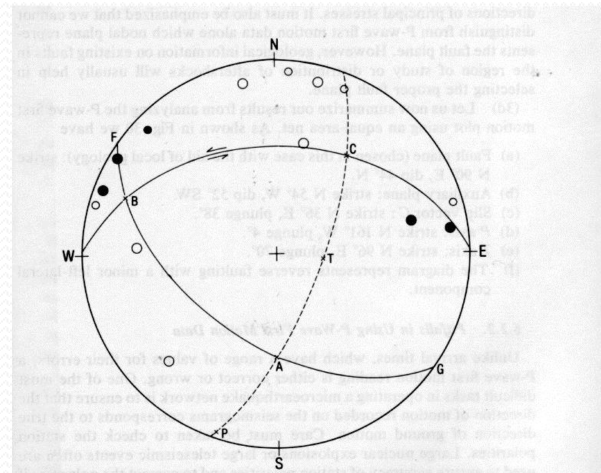
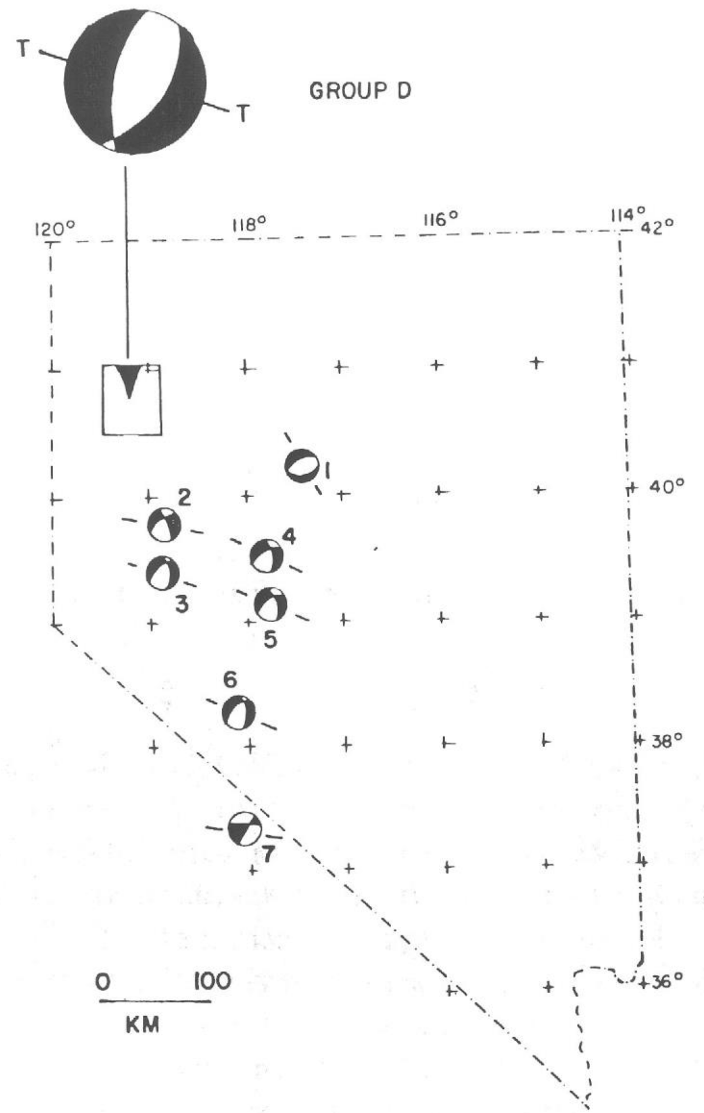


Fig. 30. A fault plane solution for a microearthquake in the Santa Barbara, California, region. The diagram is an equal-area projection of the lower focal hemisphere. See text for explanation.

When the fault plane solution observed within the small prospect area is compared with earlier more general fault plane solutions in the same area, it is possible to define if a prospect area is anomalous or typical of the region

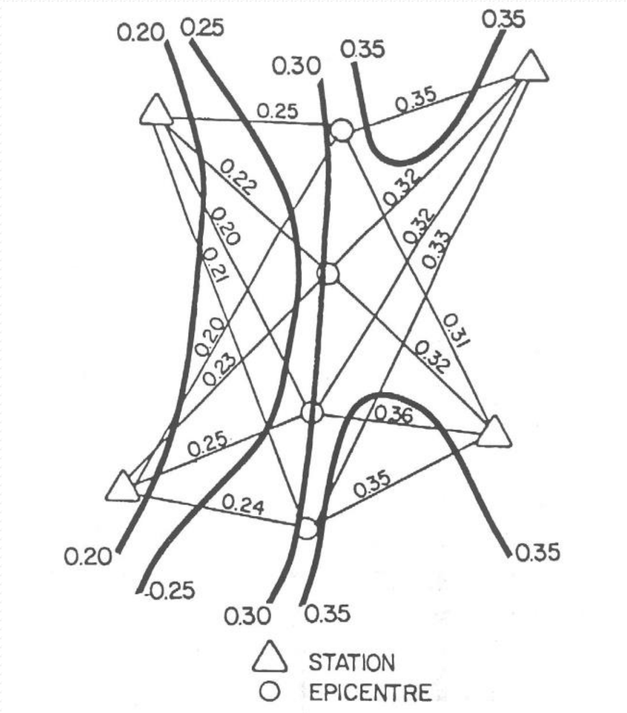


Comparison of first motion diagrams based on teleseismic data from earthquakes in Nevada and one based on local earthquake data from microseismic survey in Nevada (group D in insert). Directions of tensional stresses are uniform, indicating that events detected during the microseismic survey are probably not anomalous.

Poisson's ratio is the ratio of lateral strain to strain in the direction of stress when a cylinder of rock is subjected to uniaxial stress.

Poisson's ratio is also definable in terms of the ratio of compressional (p) to shear (s) wave velocities.

Extensive fracturing of a liquid-filled rock causes a minor reduction in the p-wave velocity and a significant reduction in s-wave velocity , producing a Poisson's ratio higher than normal.



Poisson's ratio is determined from Wadati plots. Each value is written along the assumed ray path from the epicentre to the receiver location, although there is no certainty that straight-line wave propagation took place. The significant anomaly in Poisson's ratio characterised in these data corresponds to the location of a successful geothermal well that was subsequently drilled.

Detection of P-wave delays: seismic tomography

Teleseisms, or distant earthquakes, could be used to locate large hot bodies that act as the source of geothermal systems, since an increase in temperature results in the reduction of P-wave velocity over a large volume in the crust.

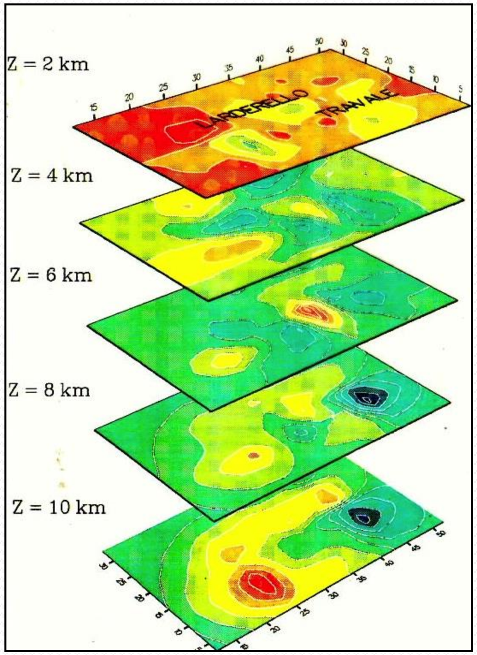
Many hundreds of P-wave arrivals must be recorded: few stations over a long period of time or a very large number of stations for a shorter period of time.

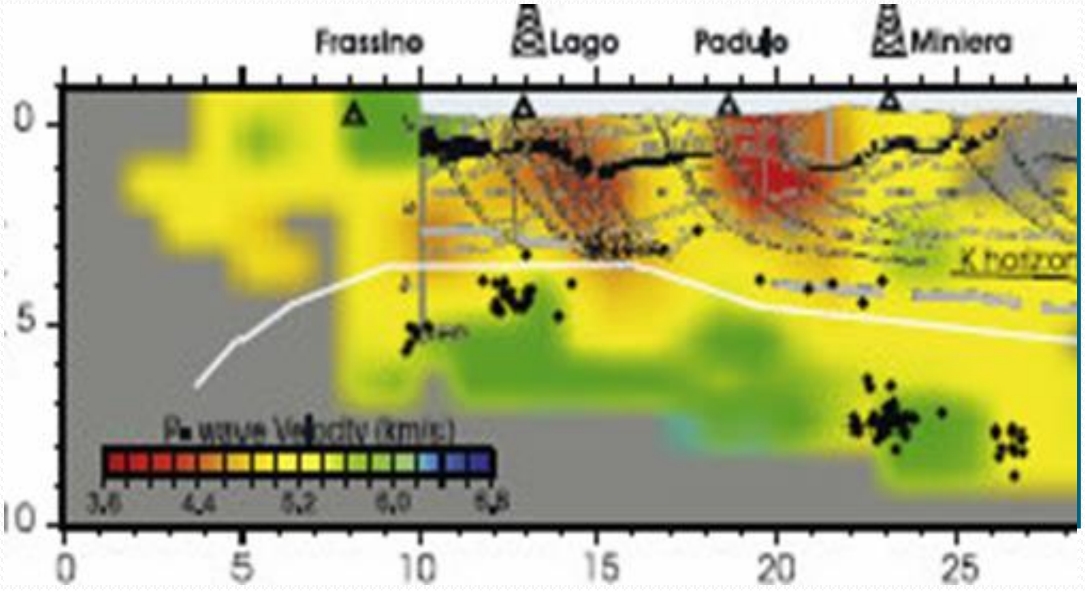
Observation of ground noise is required

The resulting seismic tomography velocity model provides information also at very deep depth.

With seismic tomography techniques it is possible to use more shallow, usually microseismic events, both naturally occurring (in seismic areas) or artificially generated, to define the velocity model at shallow depth.

Seismic tomography may help to define main velocity anomalies linked to thermal/fluid circulation effects





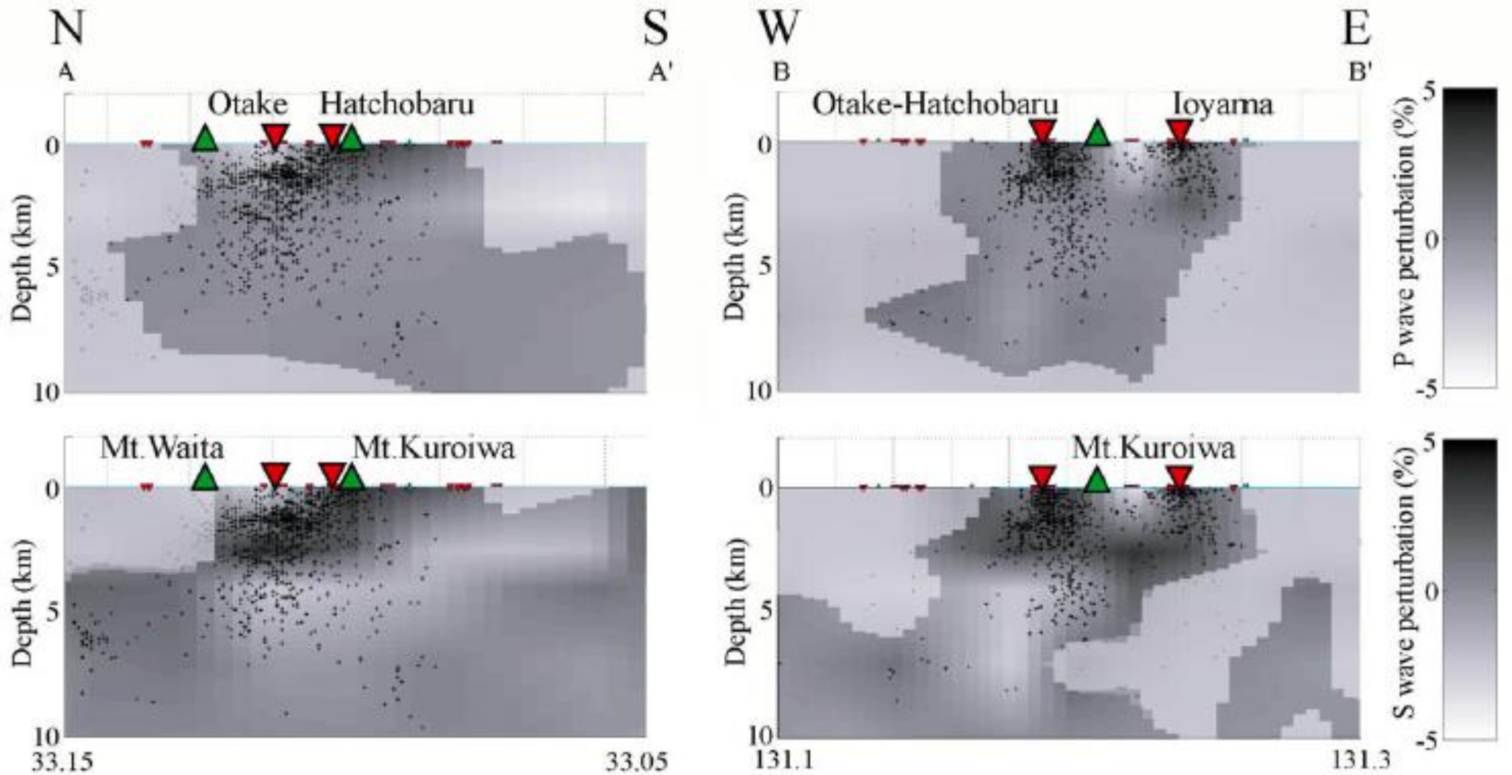


Figure 4 Cross views on A-A' and B-B' lines of perturbations of P wave and S wave velocities rounding off ±5% and hypocenter distribution near cross sections. Triangles inverted triangles and pluses on maps indicate top of mountains, hot springs and hypocenters, respectively. White zones indicate areas where CRT results are not good.

Three-dimensional seismic velocity structure of the Otake-Hatchobaru geothermal area in central Kyushu, Japan, using the tomographic method.

Yoshikawa, Sudo, Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 47 B, 2004

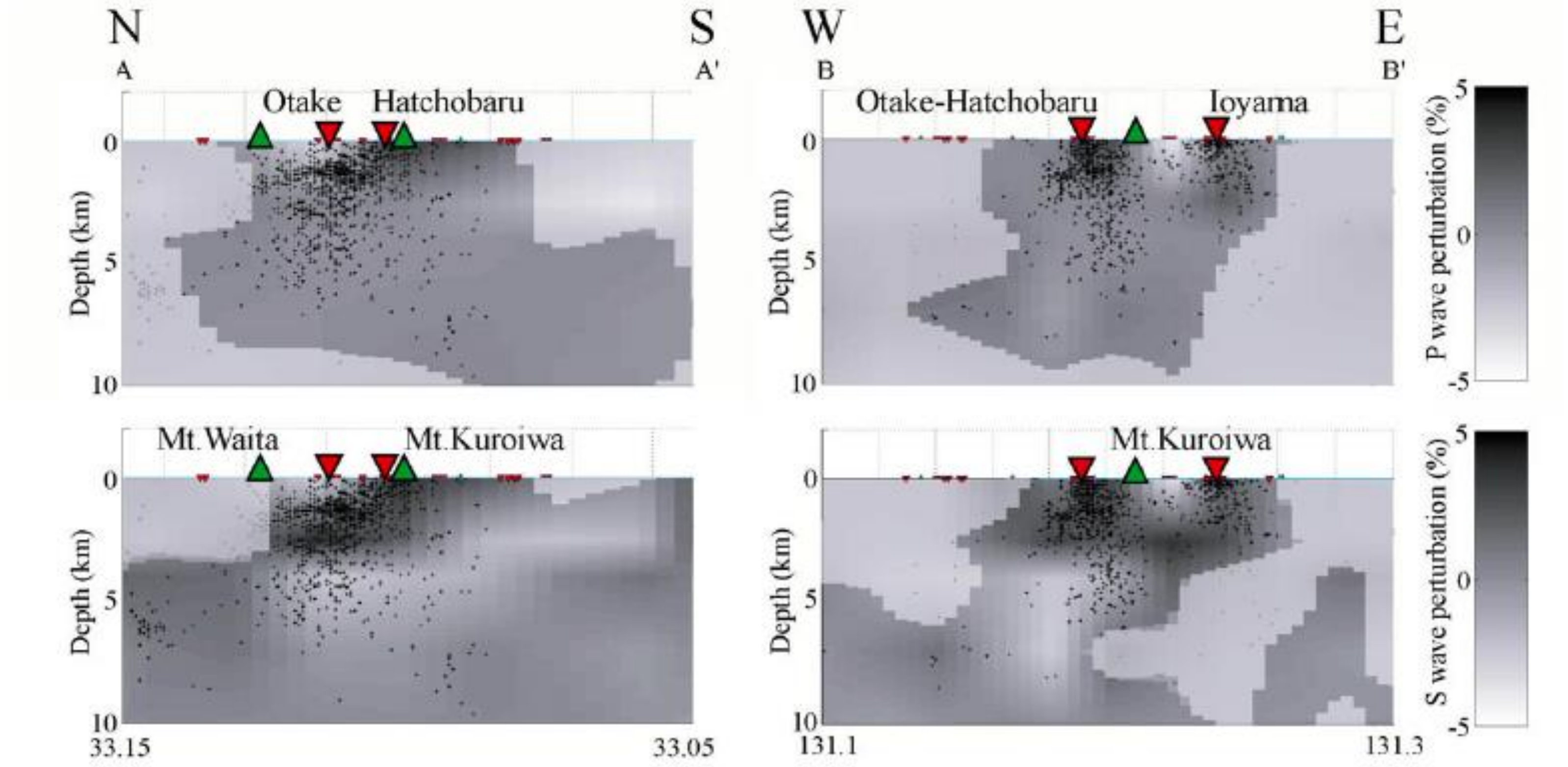


Figure 4 Cross views on A-A' and B-B' lines of perturbations of P wave and S wave velocities rounding off ±5% and hypocenter distribution near cross sections. Triangles inverted triangles and pluses on maps indicate top of mountains, hot springs and hypocenters, respectively. White zones indicate areas where CRT results are not good.

low Vs and low Vp/Vs region > 5 km = old magma body of volcanoes
the high Vs and low Vp/Vs region (Z=3.5 km depth) = granitic basement rock
low Vp and Vs regions at 1 km depth over the high Vs region = volcanic deposite zone and a fracture zone at this area.

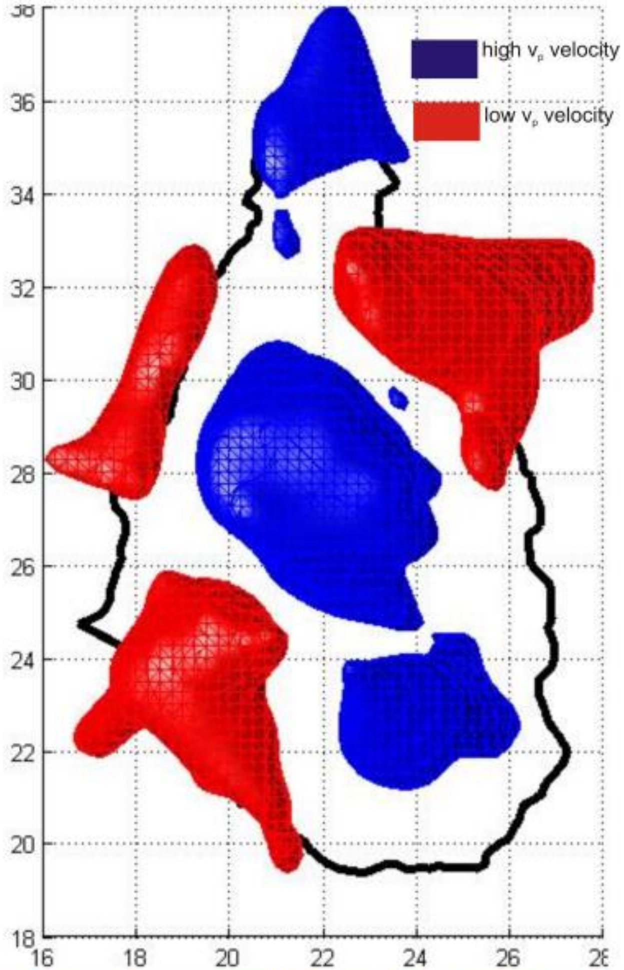


Figure 3.11: Seismic tomography map of Montserrat. Map shows areas of anomalously high and low p-wave seismic velocity (v_p)

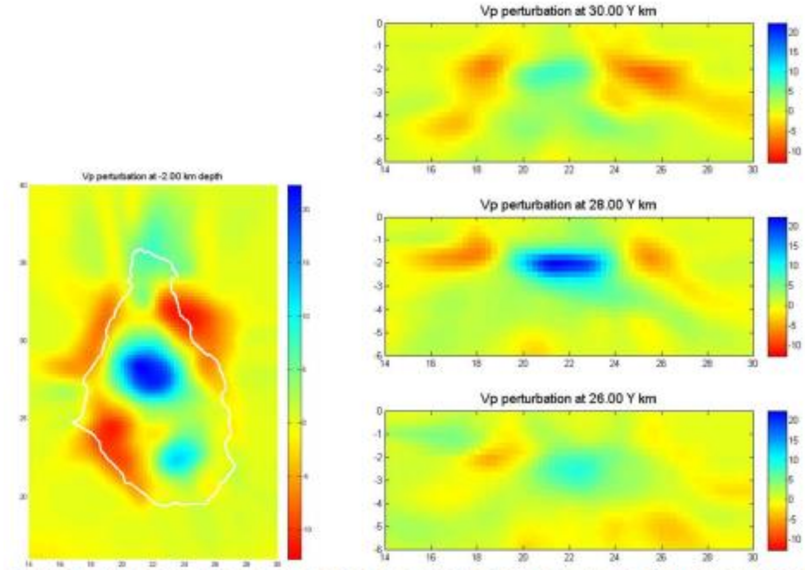
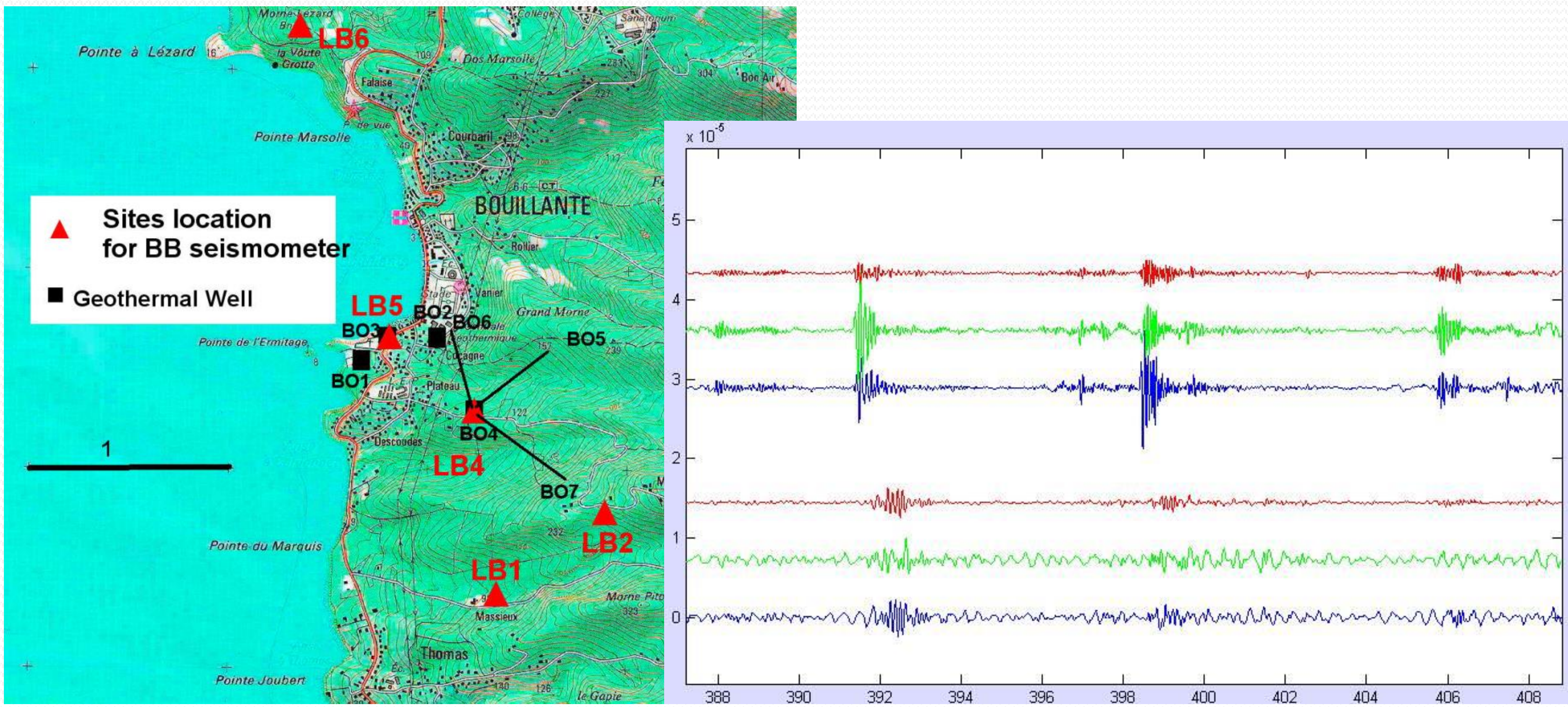


Figure 3.12: Vp perturbation at 2km depth on the left panel and cross-sections. High velocity areas are shown in blue while low velocity areas are shown in Red. Vp perturbation denotes variation in the p-wave seismic velocity away from the mean value for the area of study.

Hypocentral determination may help to define areas of hydrothermal activity.

Here is an example: Detection of long period (LP) signals related to hydrothermal manifestations (bubbling of gas in a fracture close to the surface)



Shear wave splitting

Another seismic technique used in geothermal exploration for detecting fractures and faults.

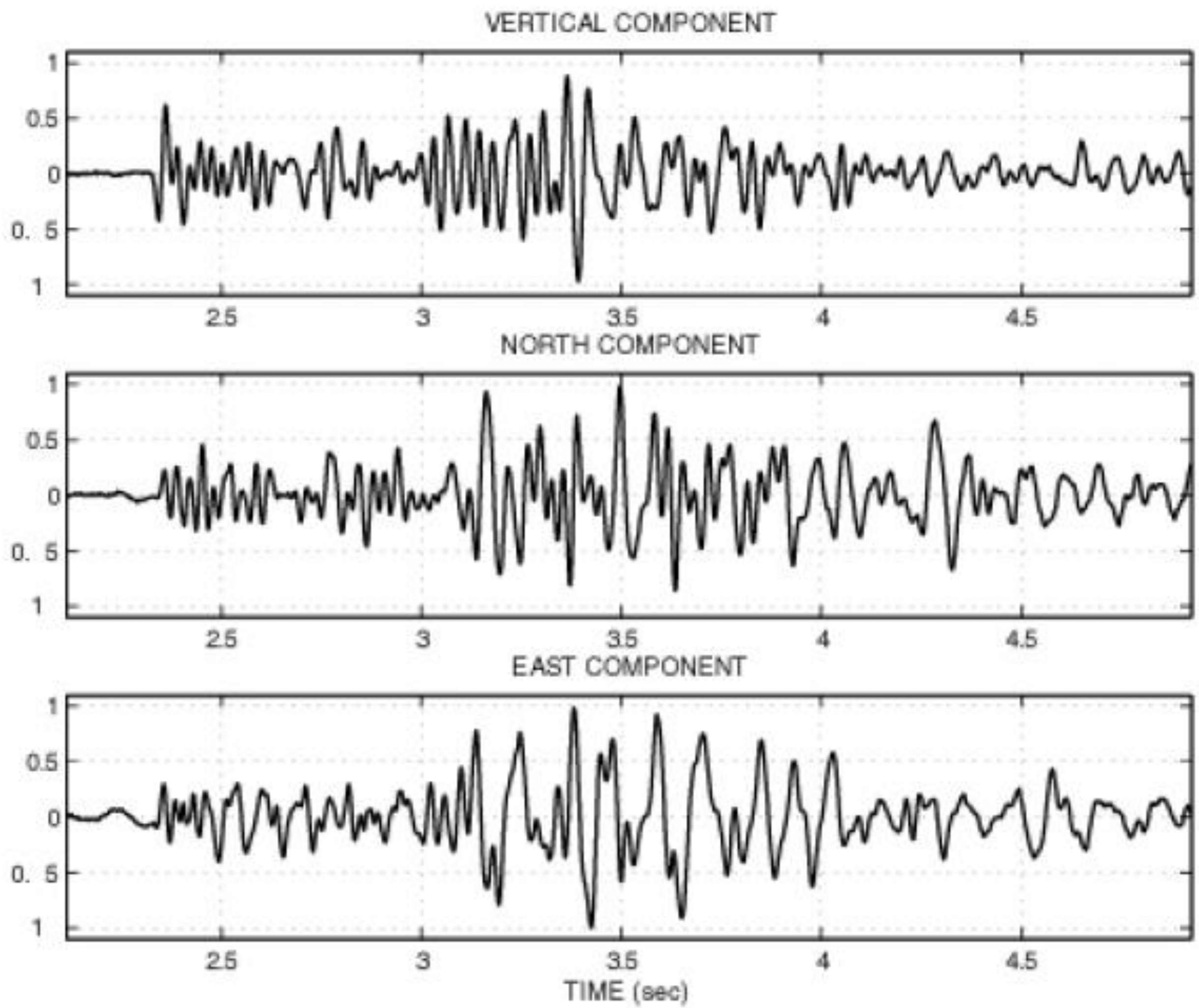
The method proved particularly effective for monitoring (time lapse recording are used as precurson of main earthquakes and volcanic eruptions or to image the effects of fluid injections in oil projects)

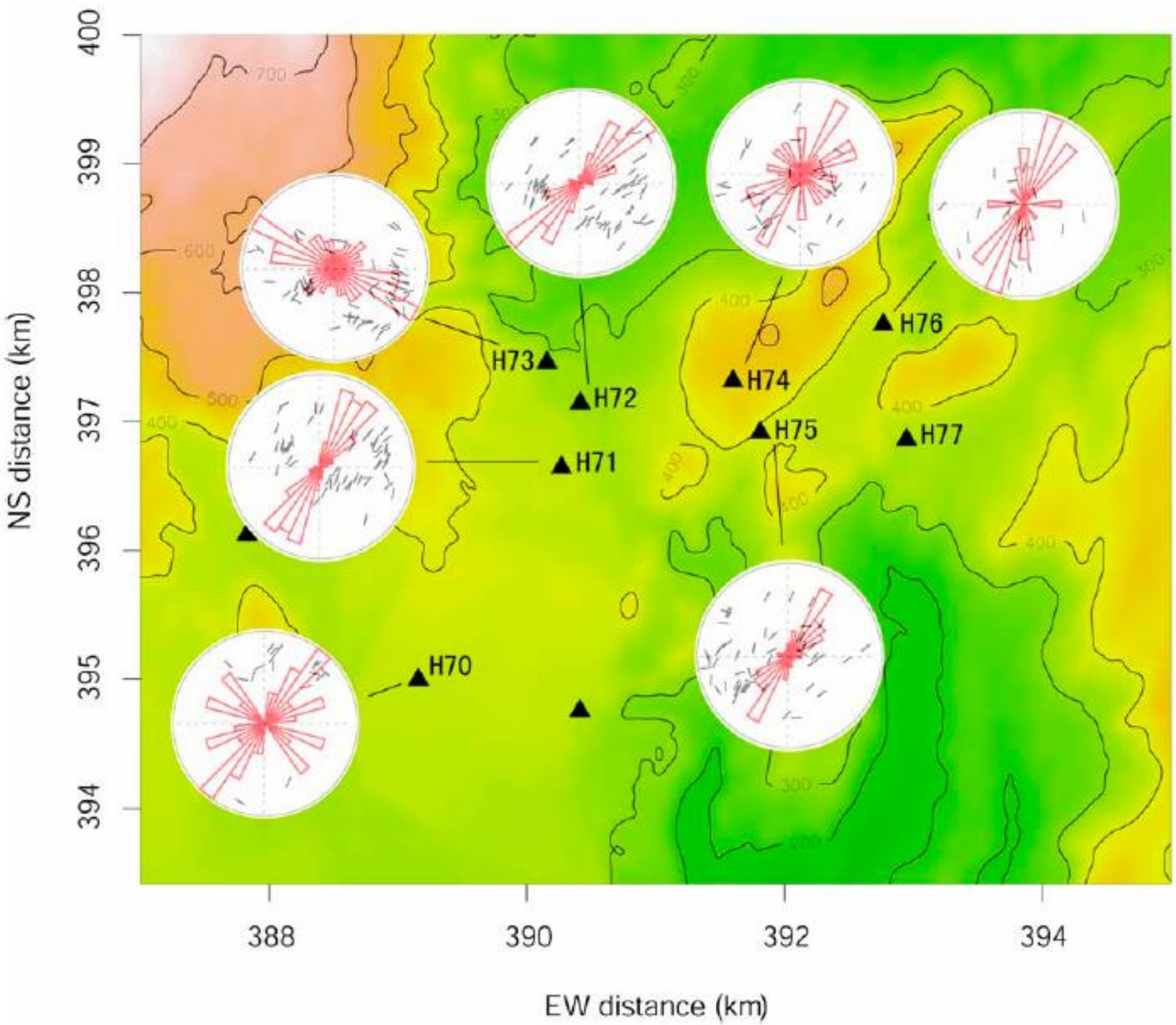
For shear wave splitting to occur the elastic properties of the rock through which the seismic waves pass must be anisotropic. In the case of geothermal systems this anisotropy is often thought to be due to the presence of **near parallel preferentially oriented fractures**.

Shear wave splitting

Anisotropy in shear wave propagation is due to variation in the bulk elastic constants in the directions parallel and perpendicular to the fracture system. Elastic constants are larger in the parallel than the materially weaker perpendicular direction. This difference in elastic constants leads to a difference in the velocity of propagation of shear waves in the two orthogonal directions.

The fast shear waves oscillate parallel to the fracture system and the slow shearwaves perpendicular to it.

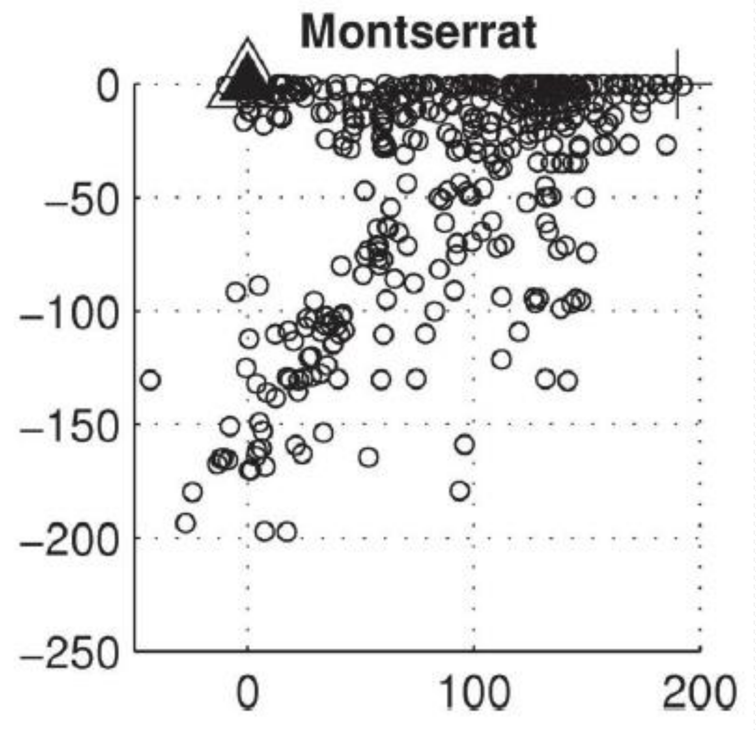

VERTICAL COMPONENT
1
0.5
0
0. 5
1
2.5
3
3.5
4
4.5
NORTH COMPONENT
EAST COMPONENT
TIME (sec)



NS distance (km)
EW distance (km)
400
399
398
397
396
395
394
388
390
392
394
700
600
500
400
300
H70
H71
H72
H73
H74
H75
H76
H77

Brittle-ductile transition

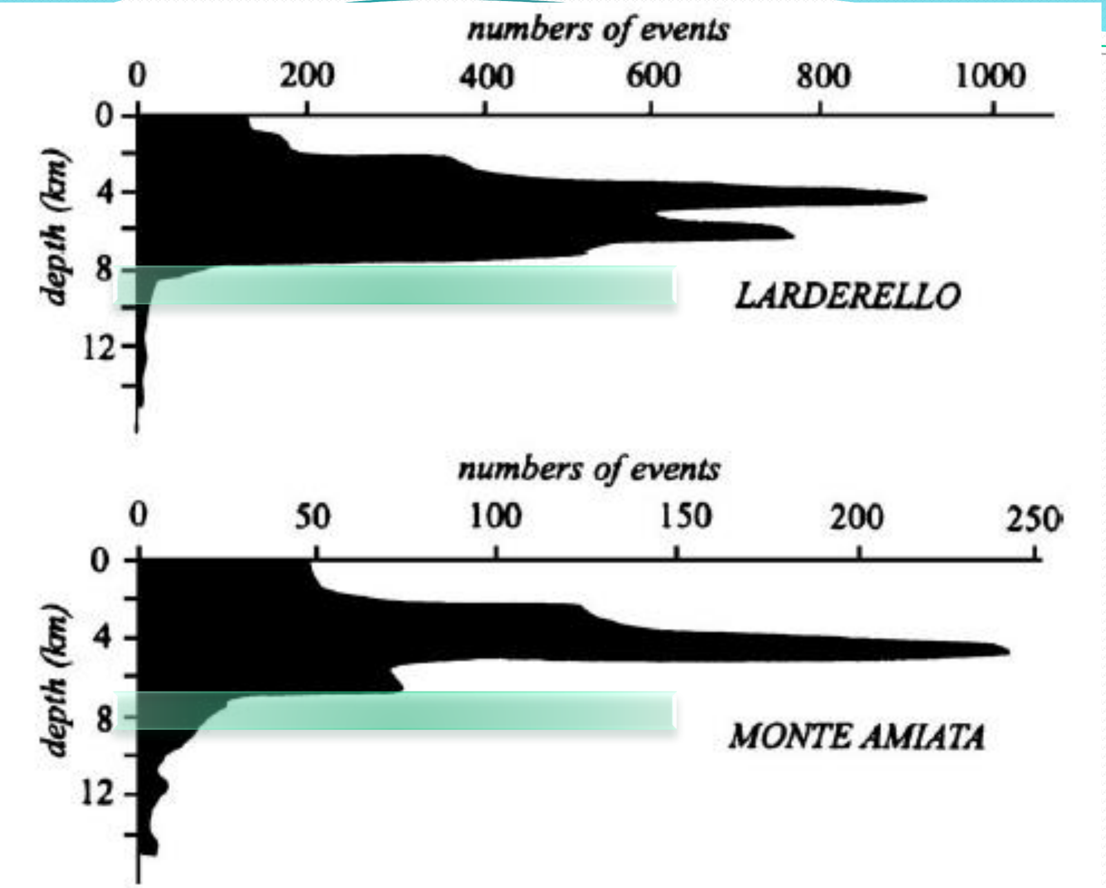
Hypocentral distribution has been used for many years to define main geodynamical and tectonic features. See, for example, the picture showing clear pattern of seismicity associated with slab subduction ranging in depth from 50 to 200 km and dipping at that the clusters of seismicity fit a 50° dip of a typical Benioff zone.
Hypocentral distribution of microearthques may also help in defining brittle-ductile transition, which in high enthalpy geothermal areas may be very shallow.



Brittle-ductile transition

Under normal conditions, there is a linear increase in the crust strength with pressure [depth] and exponential decrease in strength with temperature. Peak strength is expected at a transition point from the brittle [pressure controlled] zone called the seismogenic zone to the ductile [temperature controlled] zone, where earthquake density abruptly decline. Temperatures of less than 450° C are required for an earthquake to occur in the crust rocks.

Brittle-ductile transition is, therefore, a good indicator of temperature and in geothermal areas provide hints for the presence of heat sources (intrusive bodies)



Frequency of the hypocenters of local seismic events recorded at Larderello and Amiata vs. depth. BDT is considered the range indicated in green.

VP-VS ratio

Vp/Vs ratios are known to be sensitive to phase changes in geothermal systems. Water and steam filled pore spaces affect both P and S wave transmission differently. Vp/Vs ratios normally increase from vapour saturated [low pore pressure] condition to liquid saturated [high pore pressure] condition.

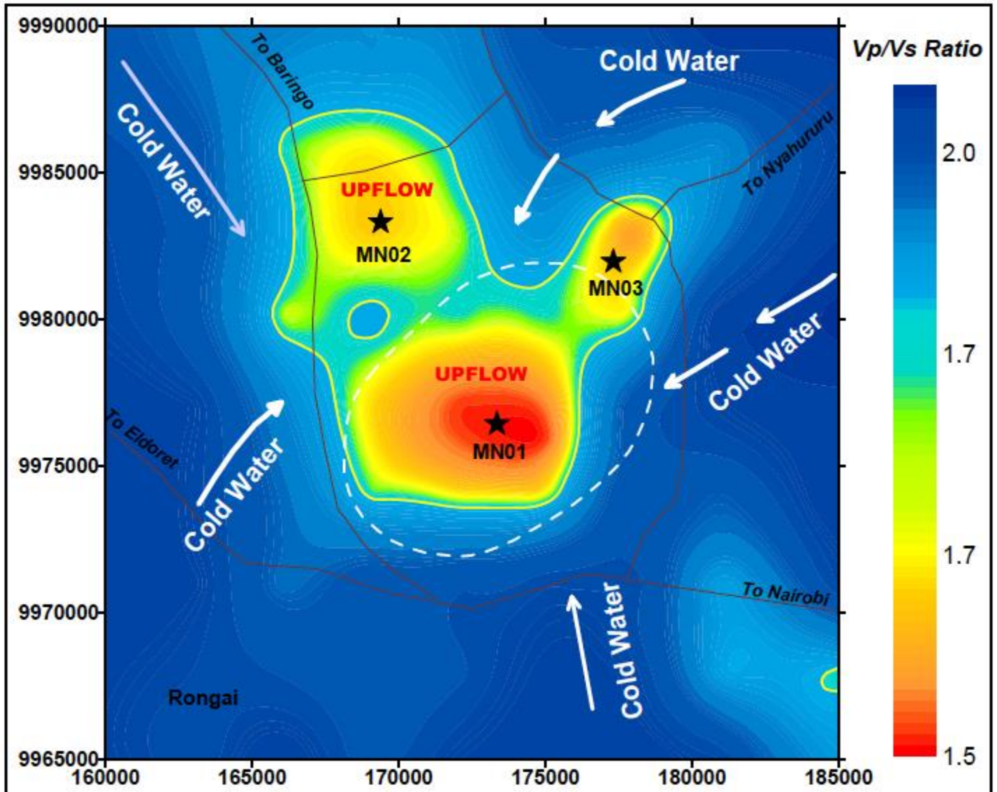


Figure 5.1. Average Vp/Vs rartion variations in the Menengai study area showing proposed test drill sites [Stars], interpreted upflow zones and fluid recharge for the system

From Simiyu 2009

Monitoring artificial MEQ

Microseismicity is often not only natural but also induced by geothermal activity. One major cause appears to be injection, which results in the reservoir rock being rapidly cooled. At the Geysers geothermal field injection has increased by about 50% the number of M=2.4 events being recorded, with no increase observed in M=2.5 events.

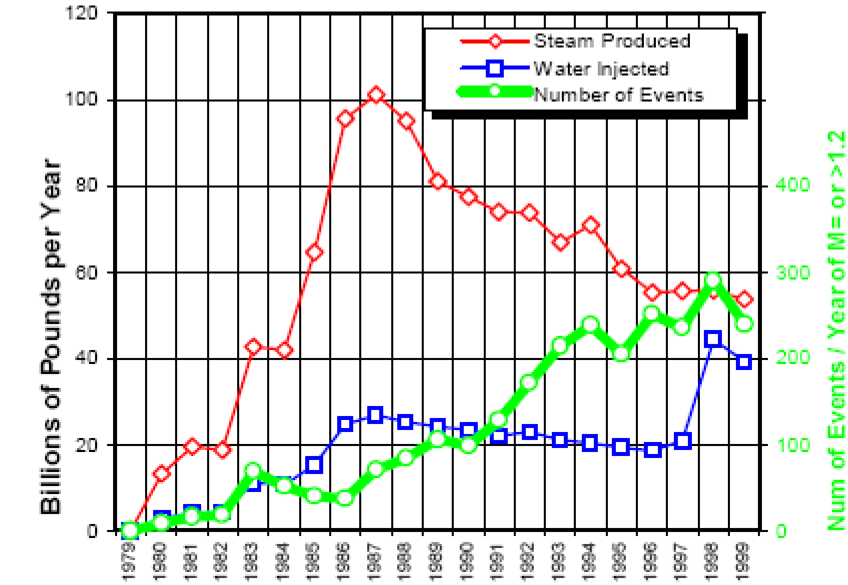


Fig.4 Annual Production, Injection & Seismicity, SE Geysers

injection effects on seismicity at Geysers geothermal field (from Smith et al., WGC2000)

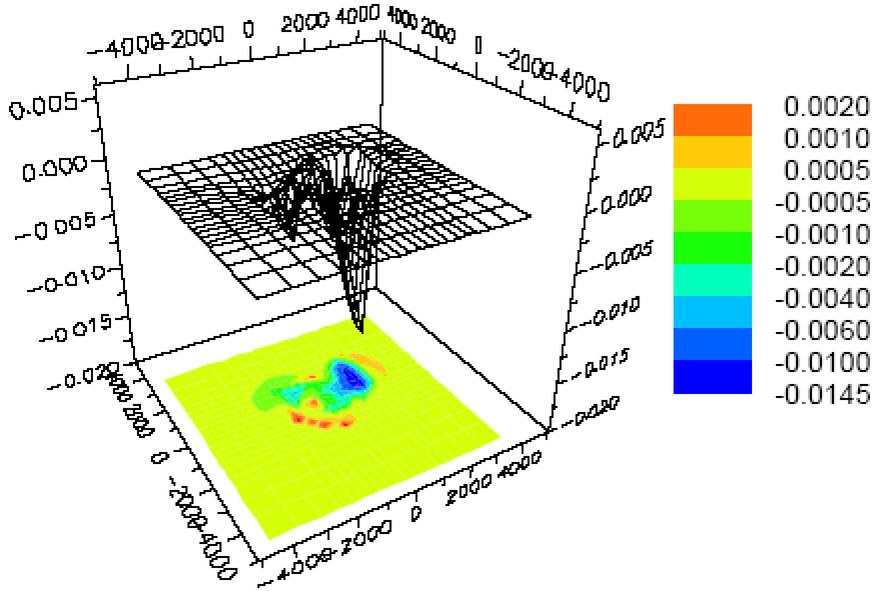


Figure 2. Travel time differences between zero and 10,000 days. The deep negative region corresponds to injection, and the high amplitude region corresponds to the edge of the steam bubble which has expanded over this time period.

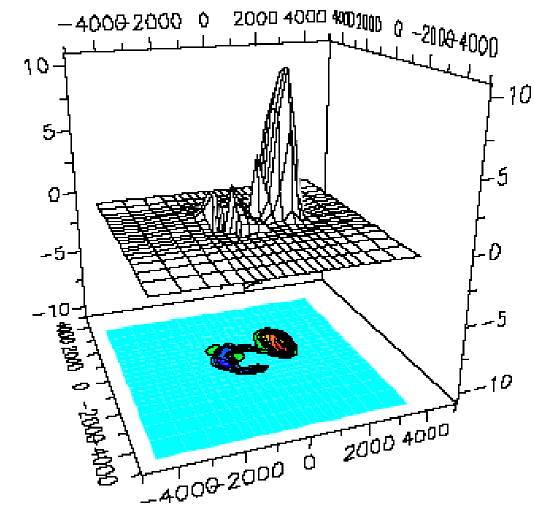


Figure 7. Depth 625-750 meters, Velocity change after 10,000 days (%).

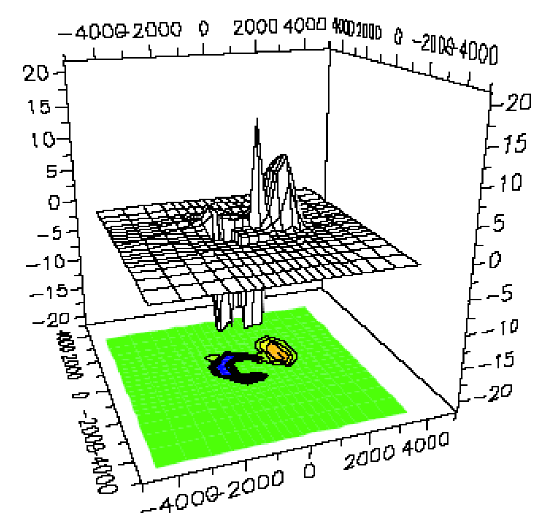
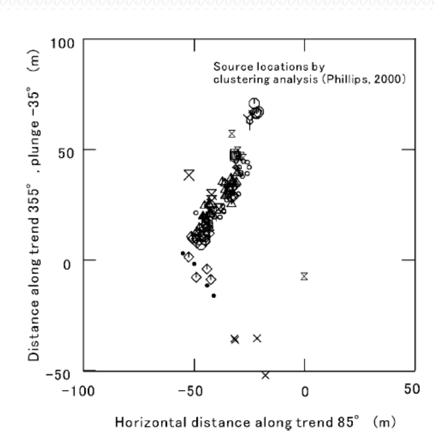
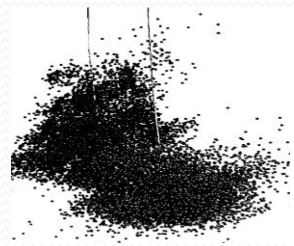


Figure 8. Depth 625-750 meters, Poisson's ratio change after 10,000 days (%).

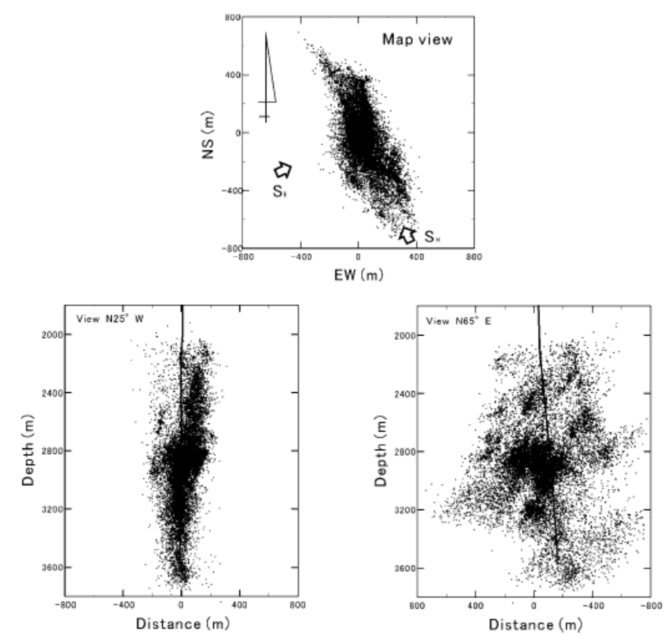
Result of a geothermal reservoir simulation from a natural state (time zero) after 10,000 days of production and injection (from Stevens et al., WGC2000).

Observing small mining produced seismic event has been called **seismic monitoring**. Events produced from fluid flow but also from internal subsidence have been successfully recorded and used to study fluid flow in time and space. Much larger events in reservoirs are generated during stimulation with artificial hydro-fracs. Monitoring the development of those fracs is usually called **fracture monitoring**. It is actually the only routinely available method to follow the development of a fracture in time and space.



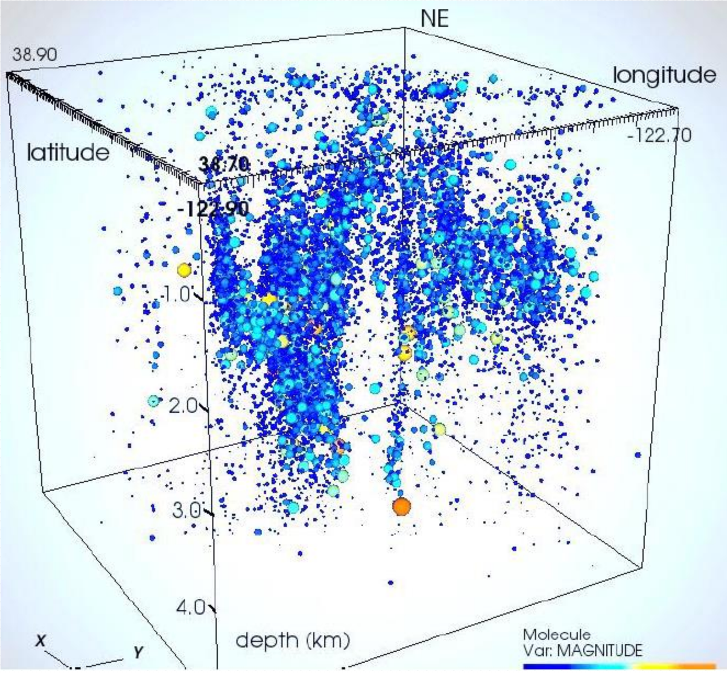


Source location in Soulz geothermal project (EGS)



Moriy, Niitsuma, Baria, Bull. Seism. Soc. Am.

Normally for the recording nearby observation wells are used. A typical distance is several hundreds of meters, but also in more than 1000m observations have been successful. Principally a singe **3-component geophone** allows locating the event. The direction is derived from a hodogram-analysis of the P-wave arrival and the distance from the P-S travel time difference. Using more than one geophone gives redundancy and thus better results. Using a **geophone array**, i.e. several 3C-geophones on different levels allows location of the events from P-wave arrivals only and avoids the often problematic and inexact reading of S-wave onsets. Drill hole and array geometry have to be modelled in advance to estimate the location accuracies.



ACTIVE SEISMIC METHODS

In active seismic methods the source is artificially provided.
Two main classes are available: reflection and refraction surveys.

Standard *seismic reflection surveys* have often yielded useful results

Seismic refraction surveys have been used to a limited extent because of the amount of effort required to obtain refraction profiles giving information at depths of 5 to 10 km, and the problems caused by the generally high degree of complexity of geological structures in areas likely to host geothermal systems.

ACTIVE SEISMIC METHODS

Seismic refraction surveys have been used to a limited extent because of the amount of effort required to obtain refraction profiles giving information at depths of 5 to 10 km, and the problems caused by the generally high degree of complexity of geological structures in areas likely to host geothermal systems.

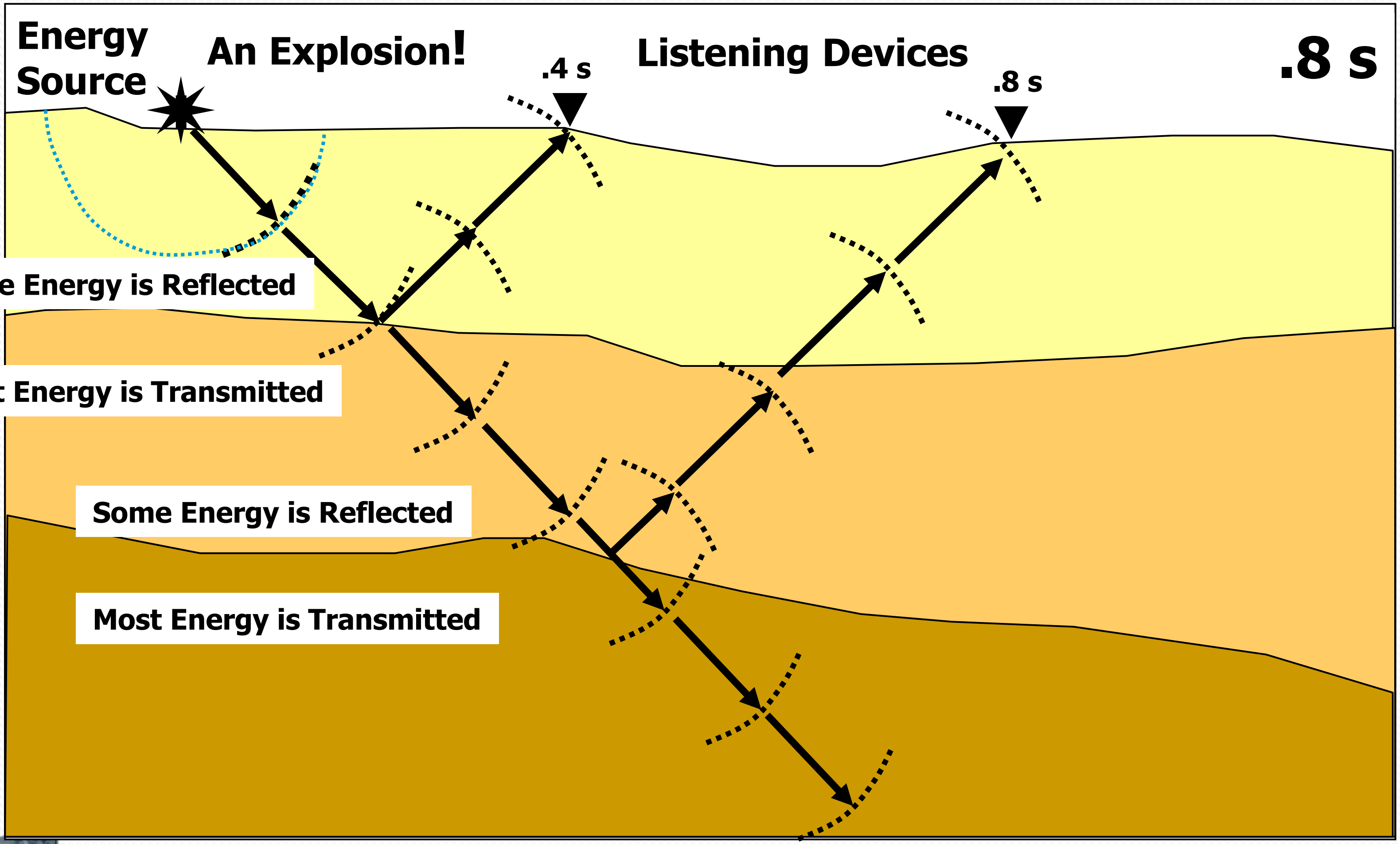
Seismic refraction is normally restricted to cases where the densities of the rocks and thus seismic **velocities increase** with depth. In addition, geophone arrays for refraction measurements need a **length of at least 4-** to 5 times (sometimes even 8 times) the sampling depth because of the very nature of refraction. The length requires higher shot energy (i.e., more explosives) and limits the applicability of refraction methods in exploration to shallower targets or to large-scale investigations of Earth's crust and upper mantle. Sometimes it can be used to get a first approximation about the velocity distribution at depth.

ACTIVE SEISMIC METHODS

Reflection seismic methods are more commonly used in geophysical exploration, as they require much shorter profiles and therefore less shot energy and have a much higher lateral resolution.

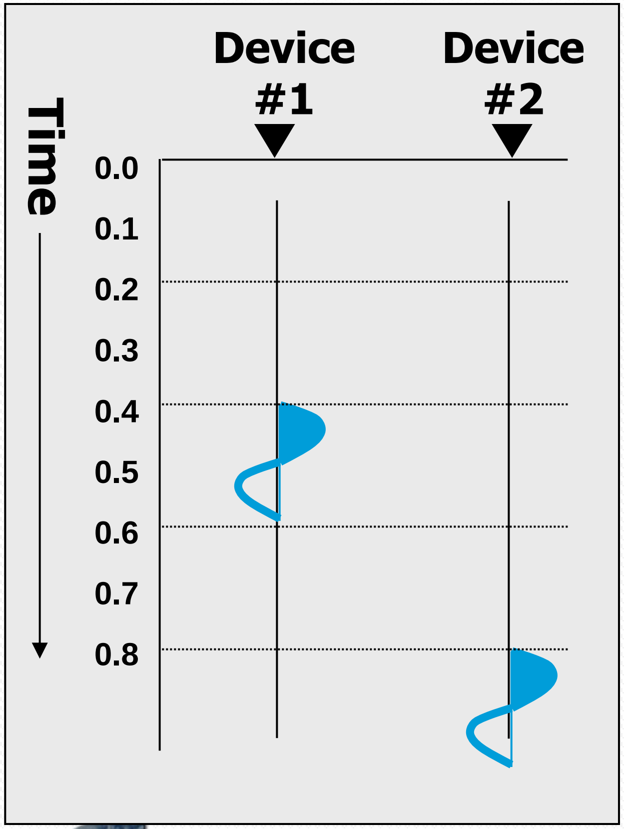
However, reflection signals are much more complex to detect and to analyse than refraction signals as they never arrive first, which implies time and labour intensive filtering and detection from a multitude of overlapping data. Moreover, the specific setup for reflection measurements requires more logistic preparation and personnel, which makes it generally a lot more expensive than refraction methods. It is nonetheless the method of choice in hydrocarbon exploration, as it can resolve structural details of a reservoir.

Reflection Seismic Method



Raw Seismic Data

To Image the Subsurface, We Use Many Shots (explosions) and Many Receivers (listening devices) Arranged in Lines on Land



Listening device #1 records a reflection starting at 0.4 seconds

Listening device #2 records a reflection starting at 0.8 seconds

Seismic acquisition

A seismic survey is designed based on:

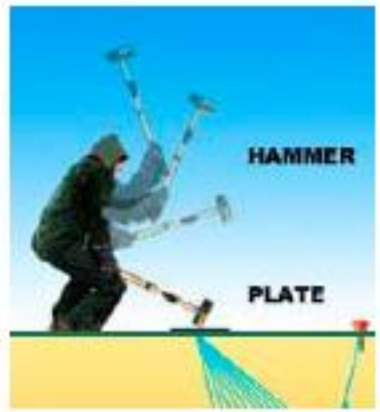
- Imaging Objectives: image area, target depth, dips, velocity, size/thickness of bodies to be imaged, etc.
- Survey Parameters: survey area, fold, offsets, sampling, shooting direction, etc.
- Balance between Data Quality & $$$$$

Seismic sources

Consider
- **Energy input**
- **Repeatability**
- **Cost**
- **Convenience**

Rifles and guns
- Cheap
- Repeatable – fire into water filled hole
- Shallow targets 0-50m

Sledge hammer
- Cheap
- Repeatable once plate is stable (and with training!)
- Targets 15-50m



Weight drops
- Cheap
- Repeatable – automated
- Targets > 50m

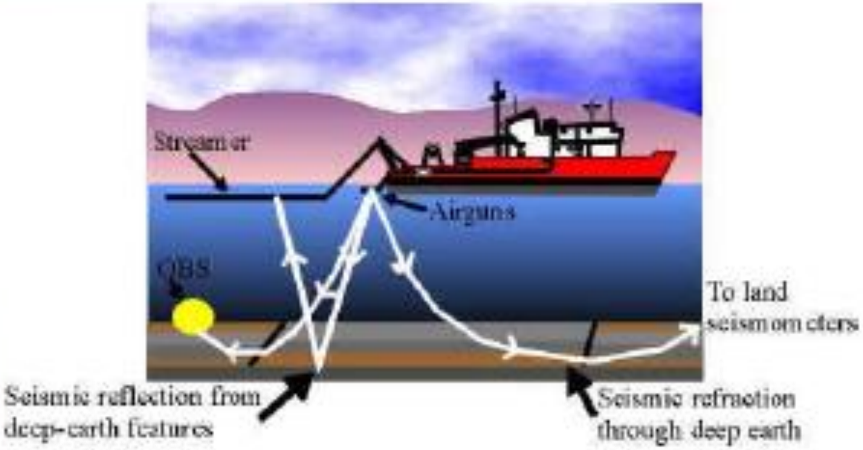
Seismic sources

Consider
- Energy input
- Repeatability
- Cost
- Convenience

Vibroseis
- No pulse, frequency sweep
- Significant signal with stacking/deconvolution

Explosives
- Various sizes – target depth
- Safety and expense can be an issue

Air guns
- At sea
- Very repeatable
- Large array for big signal



Source spectrum

This is the range of frequencies within the source pulse

Try to avoid frequencies where there is significant noise e.g. 50 Hz

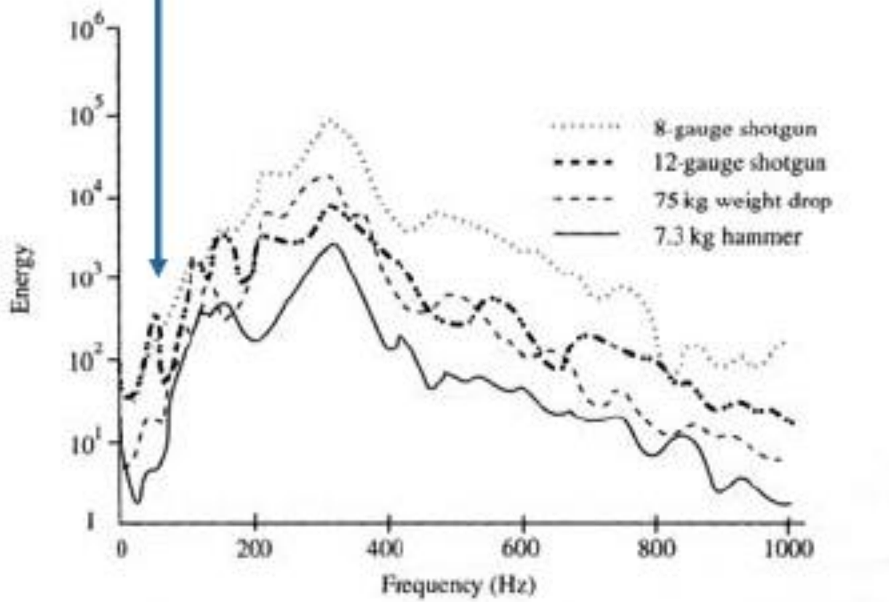


Figure 2-26 A comparison of relative energies and frequency content for shotgun and weight-drop seismic sources.

Sources:

Shotgun

Hammer

Explosive

Air gun

higher to lower frequency

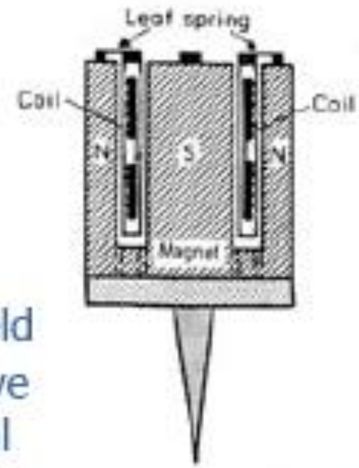
Non-explosive source such as the Vibroseis are more common (explosives are not practical with close villages and in volcanic rocks)

In Vibroseis approach, an oscillatory sound wave, which varies in frequency over the duration of a single transmission, is transmitted through the ground.

Frequency is normally swept from a high of 60 – 80 Hz to a low of 6 – 8 Hz, with the duration of the sweep being 8 – 10 s.

In order to obtain recognisable signals at an array of geophones a short distance away, many transmissions are stacked.

Seismic receivers



Geophones

- Cylindrical coil suspended in a magnetic field
- The inertia of the coil causes motion relative to the magnet generating a electrical signal
- Geophones are sensitive to velocity

Hydrophones

- Used at sea
- Use piezoelectric minerals to sense pressure variations

Instrument response

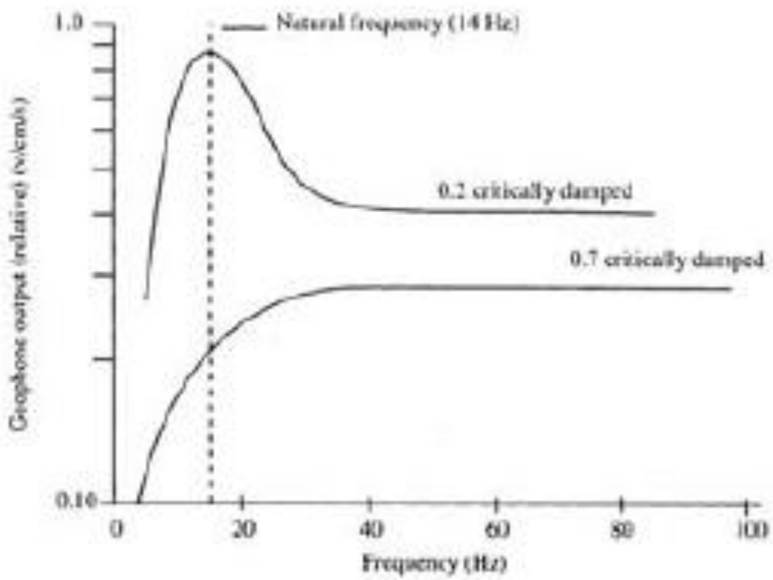
- The relation between the input ground motion and the output electrical signal

Natural frequency

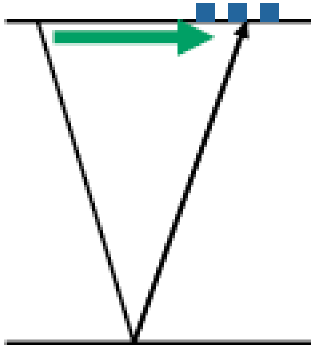
- The frequency which produces the maximum amplitude output

Damping

- Reduces the amplitude of the natural frequency response and prevents infinite oscillations
- Want a **flat response**



Deployment



Important considerations

- Need good coupling to the ground – spike
- Mini-arrays to reduce surface wave noise

Offset of geophones

Small offsets

- Near-vertical incidence retains P-energy
- High resolution of subsurface reflectors

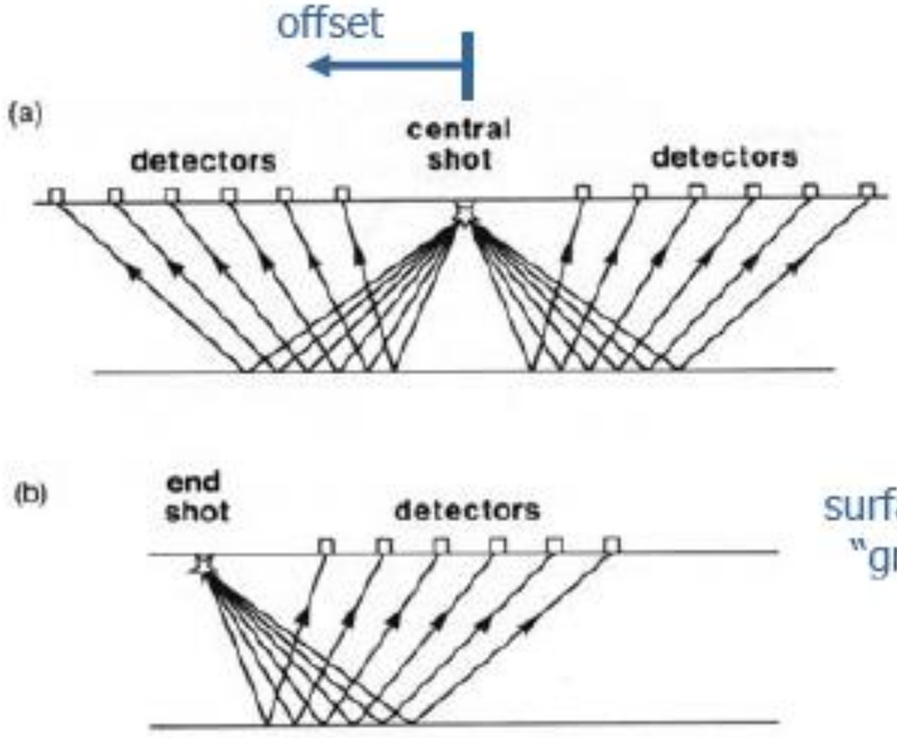
➔ **Seismic reflection analysis**

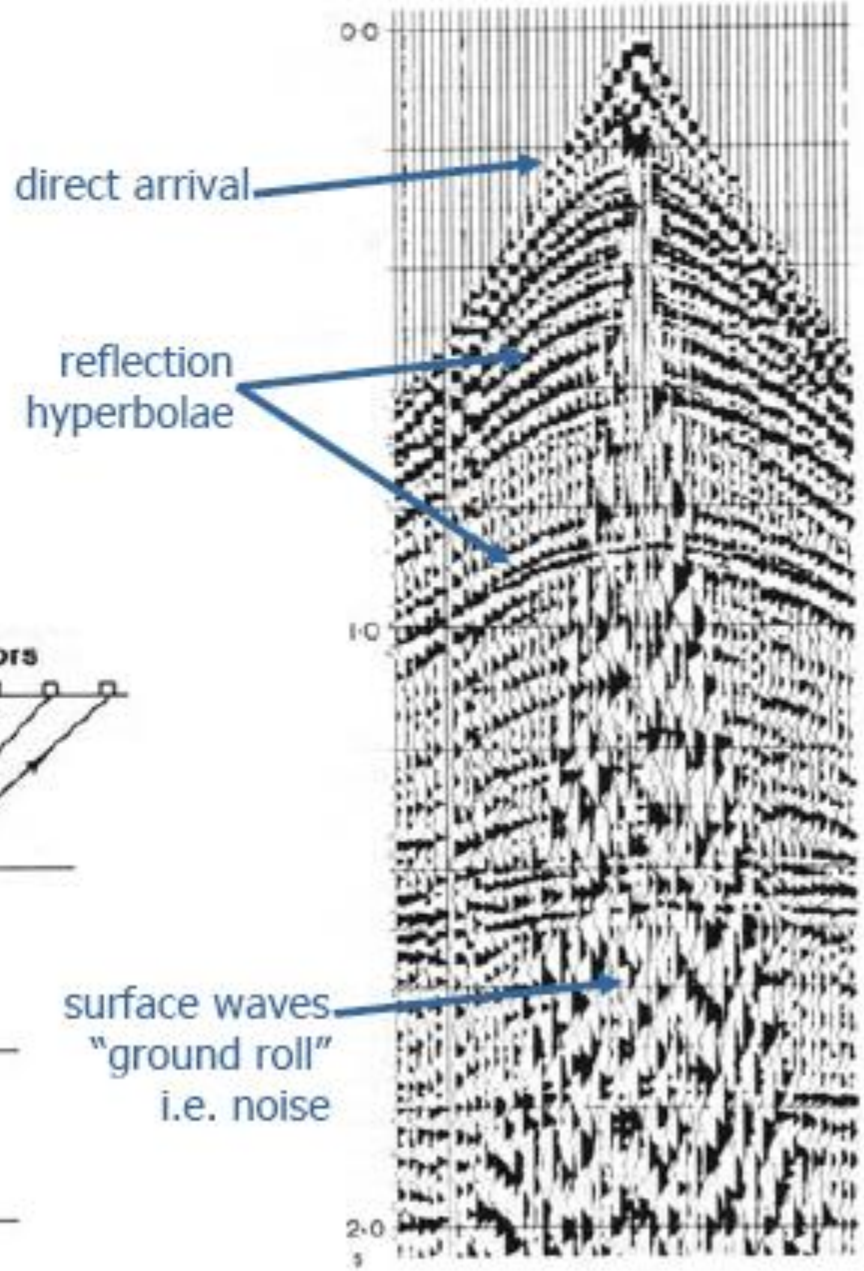
Large offsets

- Improves velocity sensitivity
- Provides horizontal averages only

➔ **Seismic refraction analysis**

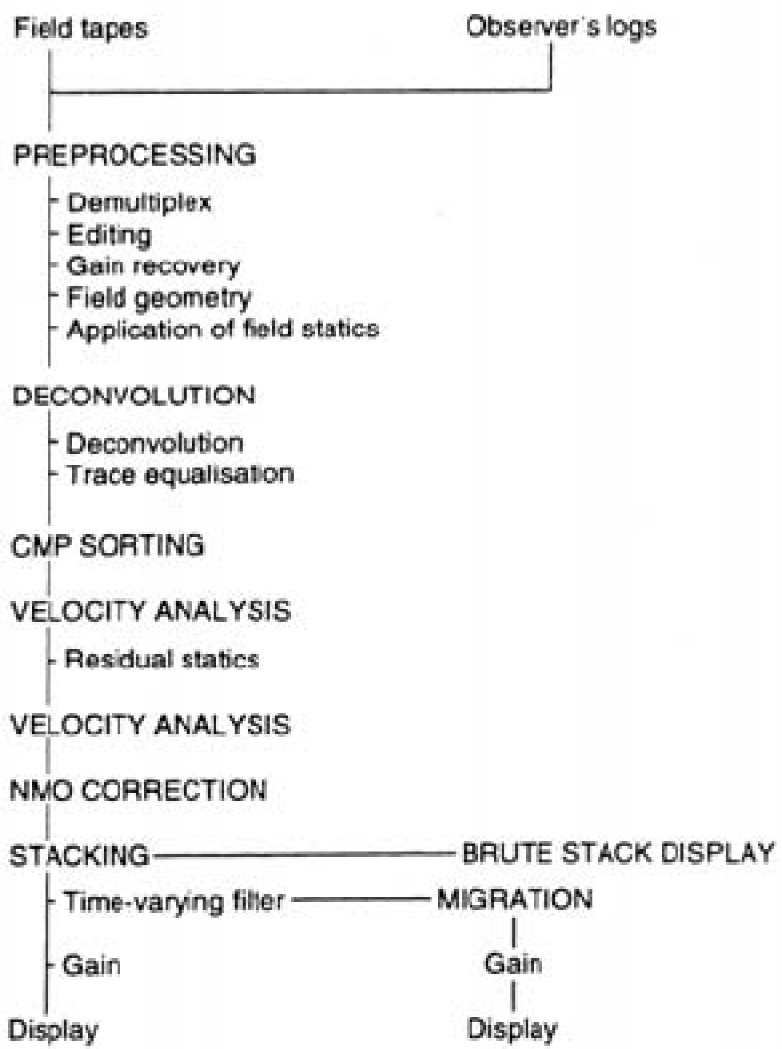
Shot gathers





Seismic reflection processing

Flow overview



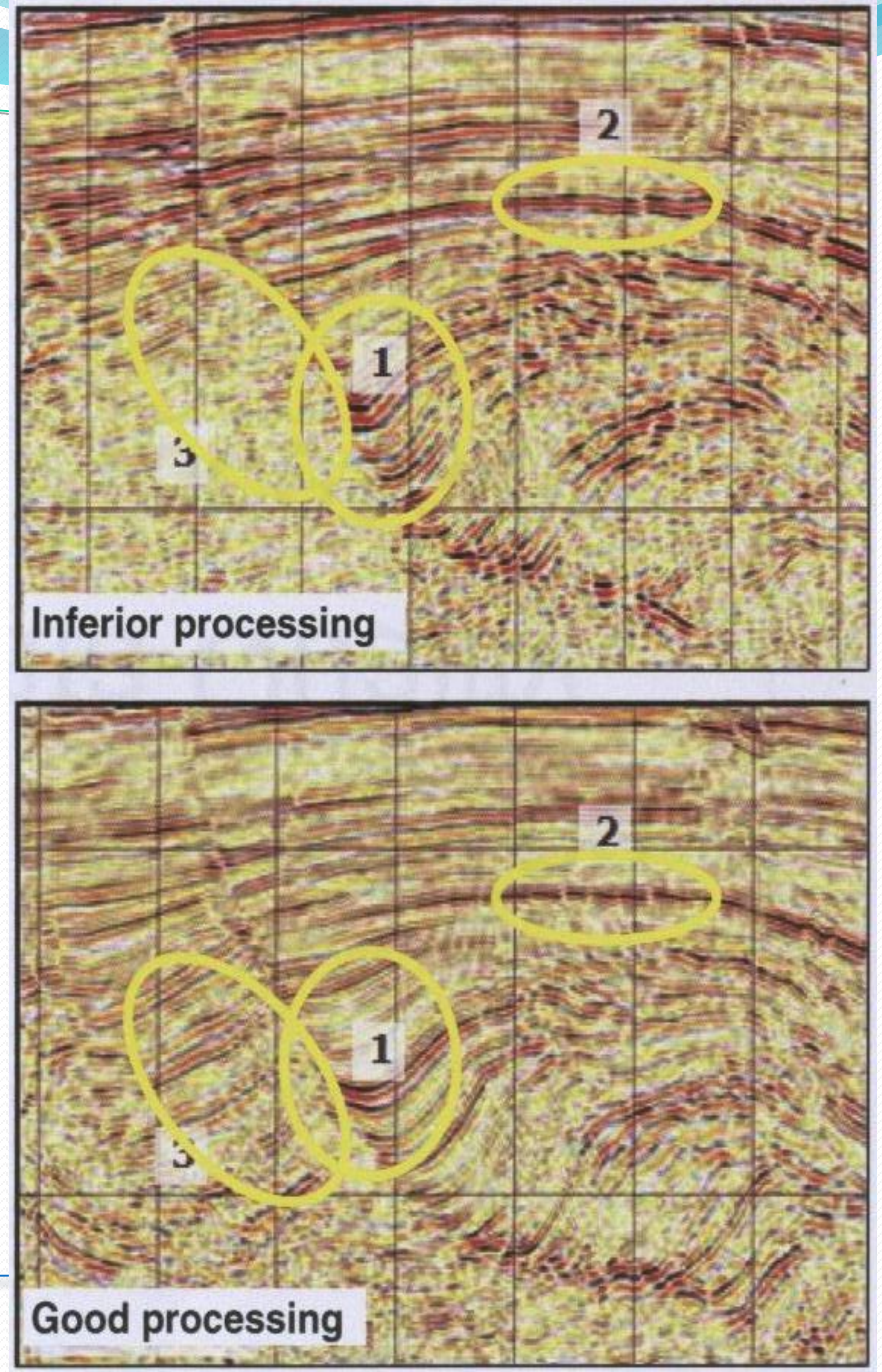
These are the main steps in processing

The order in which they are applied is variable

Seismic processing objectives

- To produce accurate subsurface images:
- Correct geometry /amplitudes (i.e. to remove distortions due to wave propagation)
- Noise attenuation: enhance S/N

In synthesis:
recover true Earth response to stress applied at the surface

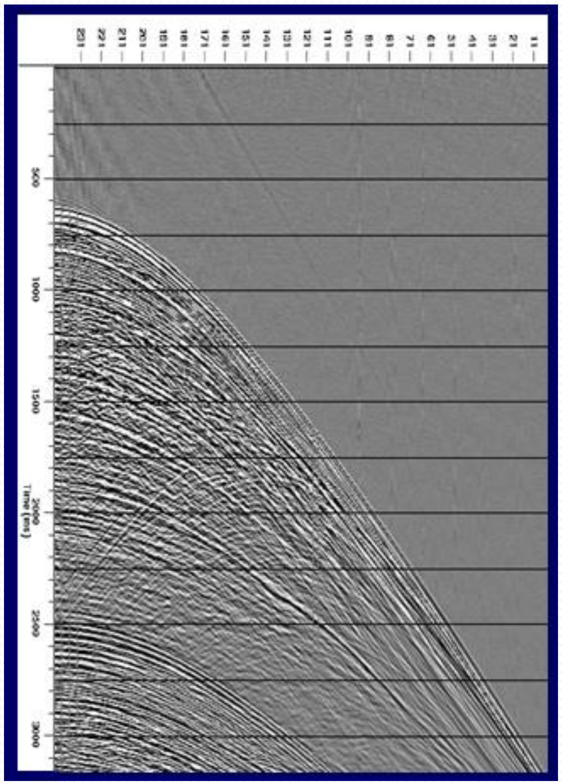


The seismic tools

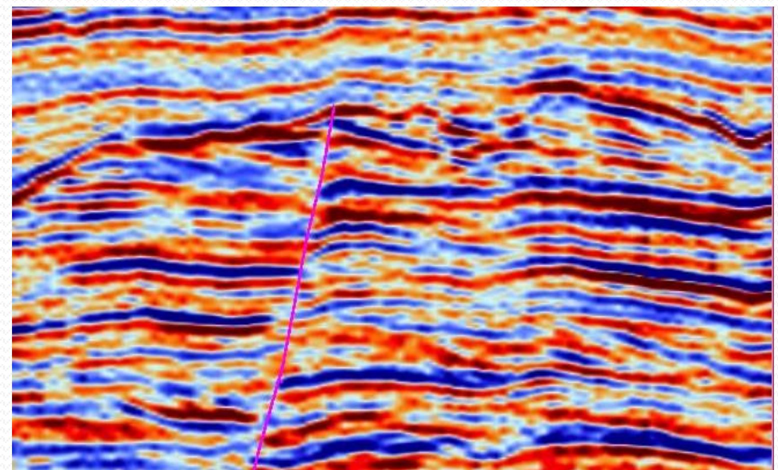
Kinematic: arrival time, velocities

Dynamic: amplitude

Data Processing Stream



Field Record



Subsurface 'Image'

Normal move out (NMO)

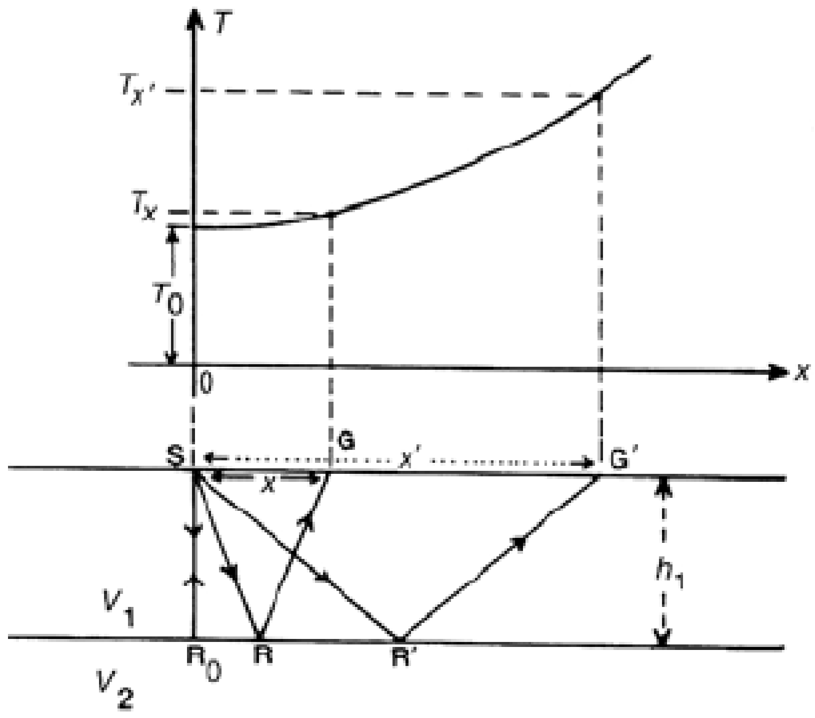
Reflection from a single horizontal impedance contrast:

Arrival time

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

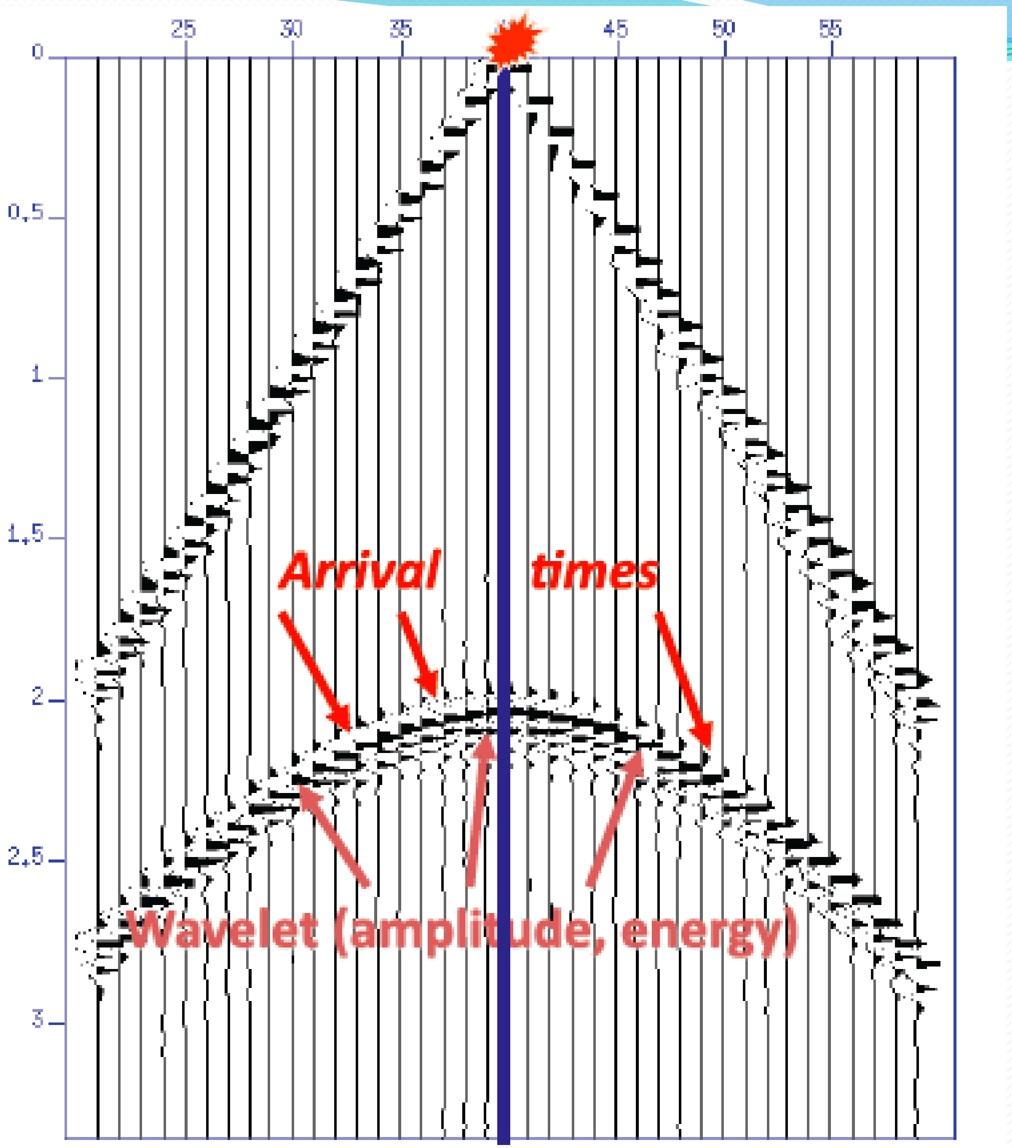
or

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



The arrival time curve is a hyperbola

Note: a geophone spread GG′ samples RR′ of the reflector. RR′=GG′/2


25
30
35
45
50
55
0
0,5
1
1,5
2
2,5
3
Arrival
times
Wavelet (amplitude, energy)

Multiple layers

Use Snell's Law to trace ray paths

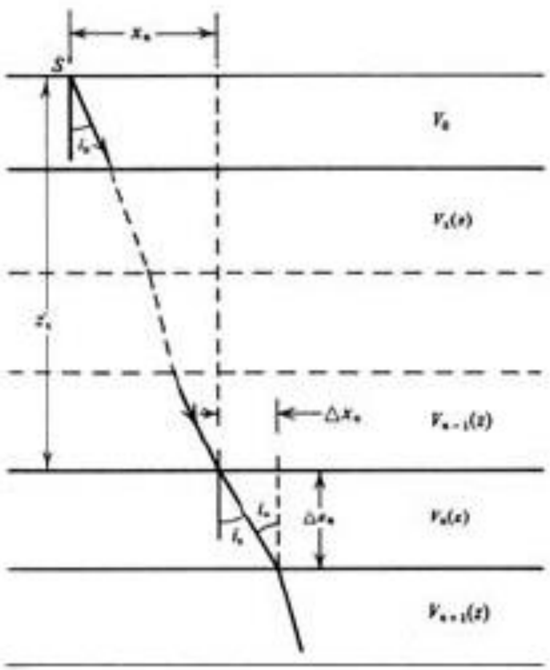
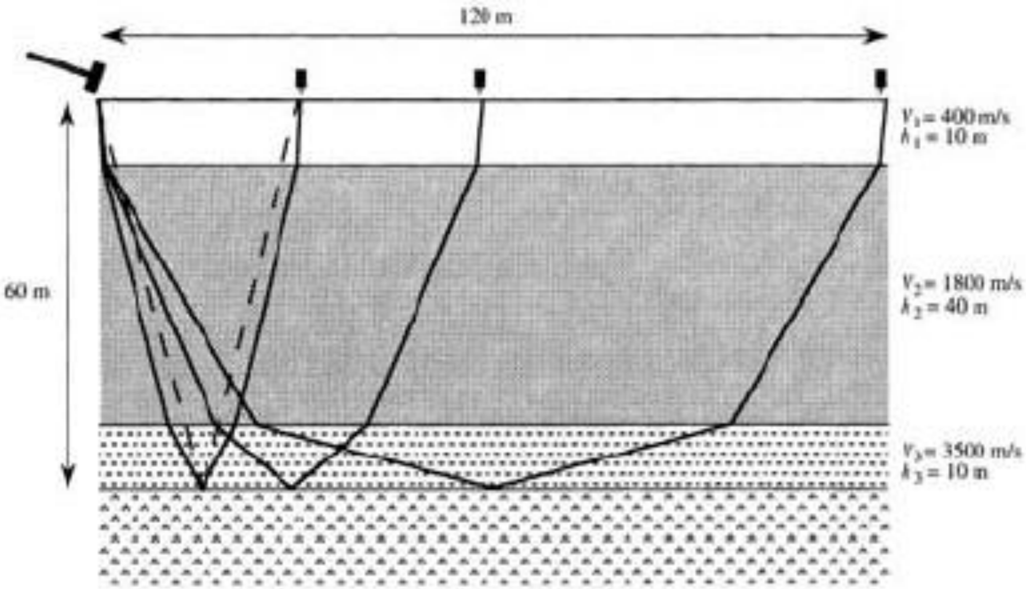


Figure 4.29. Raypath where velocity varies with depth.



At each interface

$$\frac{\sin i_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}} = p$$

NMO for layers

When the offset is small w.r.t. reflector depth (x<<h), the NMO curve is still a hyperbola

$$T^2 = T_{0,n}^2 + \frac{x^2}{\overline{V}_{rms,n}^2}$$

where

$$T_{0,n} = \sum_{k=1}^{n} T_{0,k} = \sum_{k=1}^{n} \frac{2h_k}{V_k}$$

$$\overline{V}_{rms,n}^2 = \frac{\sum_{k=1}^{n} V_k^2 T_k}{\sum_{k=1}^{n} T_k}$$

Determine velocity structure one layer at a time

k=1

k=2

k=3

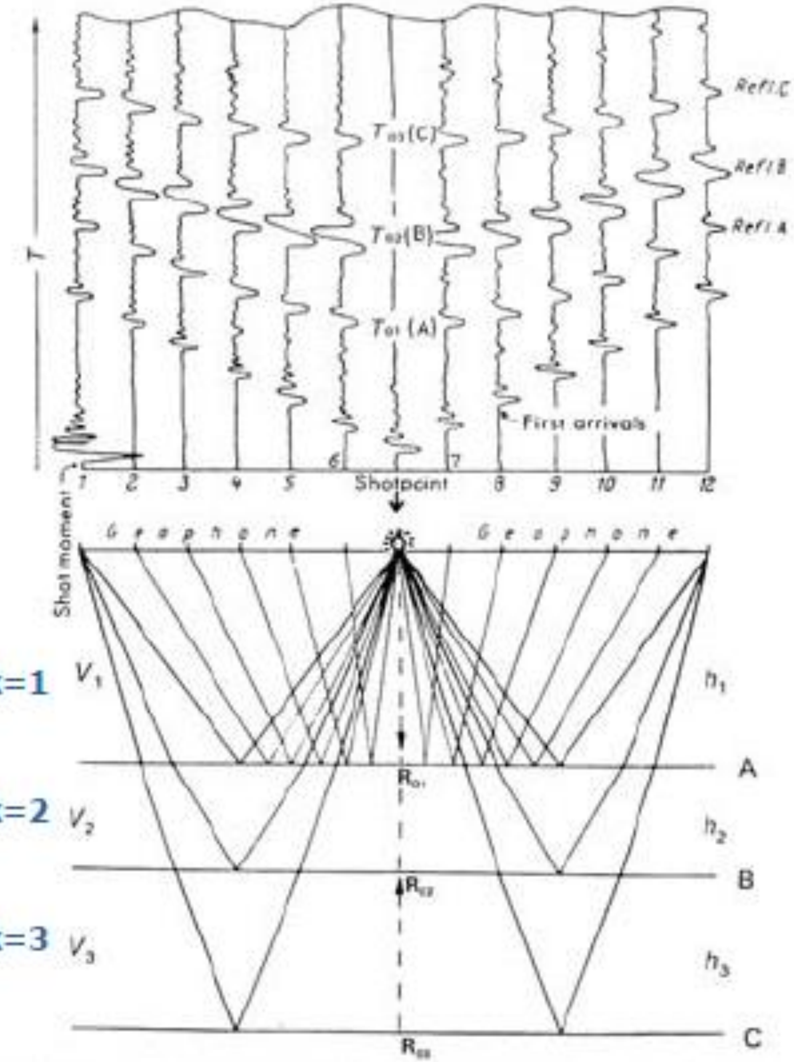
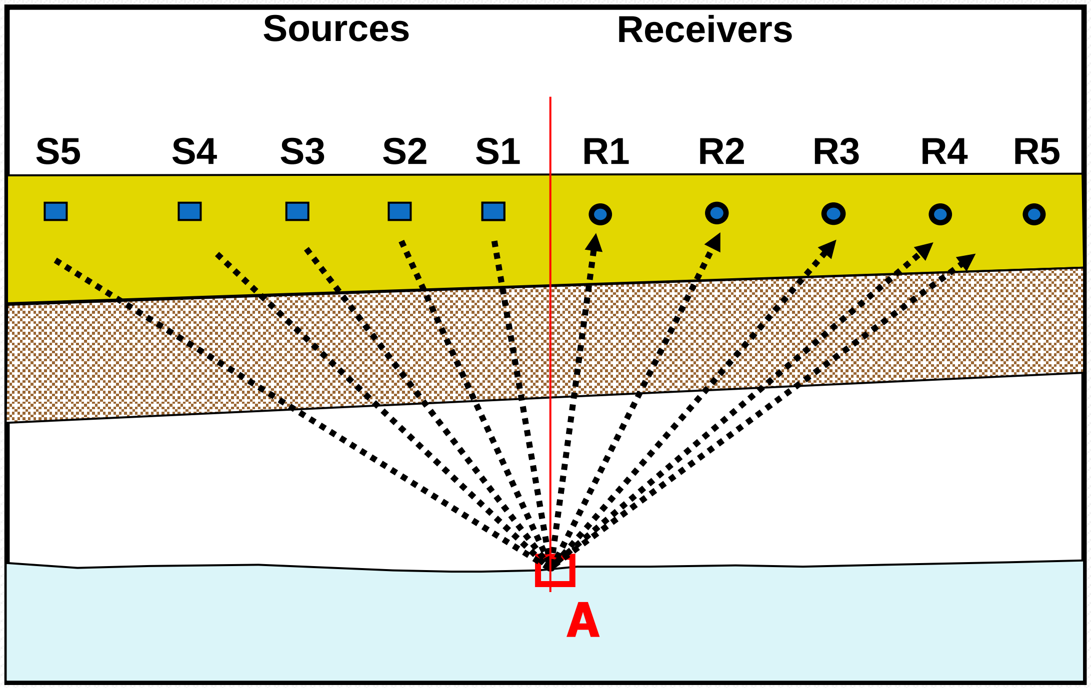
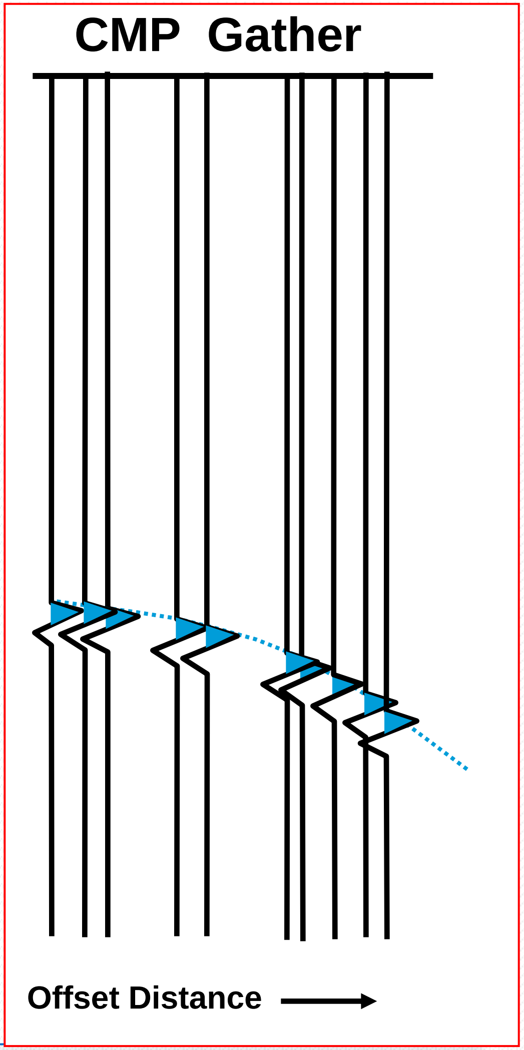


Fig. 4.14 Schematic diagram showing the production of a reflection seismogram. The 12-trace record shows the time sequence of the reflected pulses from reflecting horizons A, B, and C. T_{01}, T_{02}, and T_{03} are the two-way vertical travel-times from points R_{01}, R_{02}, and R_{03}, respectively, below the shotpoint. The significance of first arrivals is discussed in Section 4.4.5.

Common Midpoint Gather



We sort the shot-receiver pairs so that data from the same 'bounce' point (e.g., at 'A') is captured



Choosing the suitable pairs of shot and data-channel as shown the figure, the reflection time series (seismic traces) data set which transmited through the "same" reflection point may be collected.
The point is called as Common Mid Point, CMP (sometimes as Common Depth Point, CDP, too).

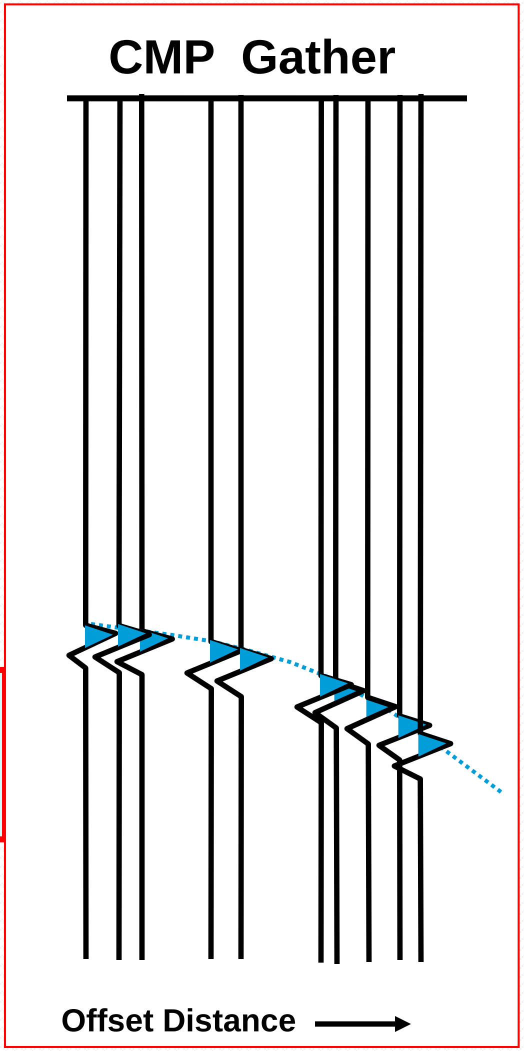
In analysing the ray paths, it can be seen that reflections are obtained from the same point in the subsurface with different separations between the vibrator and the geophones. Data quality can be enhanced by synchronously adding reflections that arrive from the same reflection point on a subsurface interface, but in so doing corrections must be made for the difference in travel times that is associated with the difference in separation from transmitter to receiver.

CMP Gather

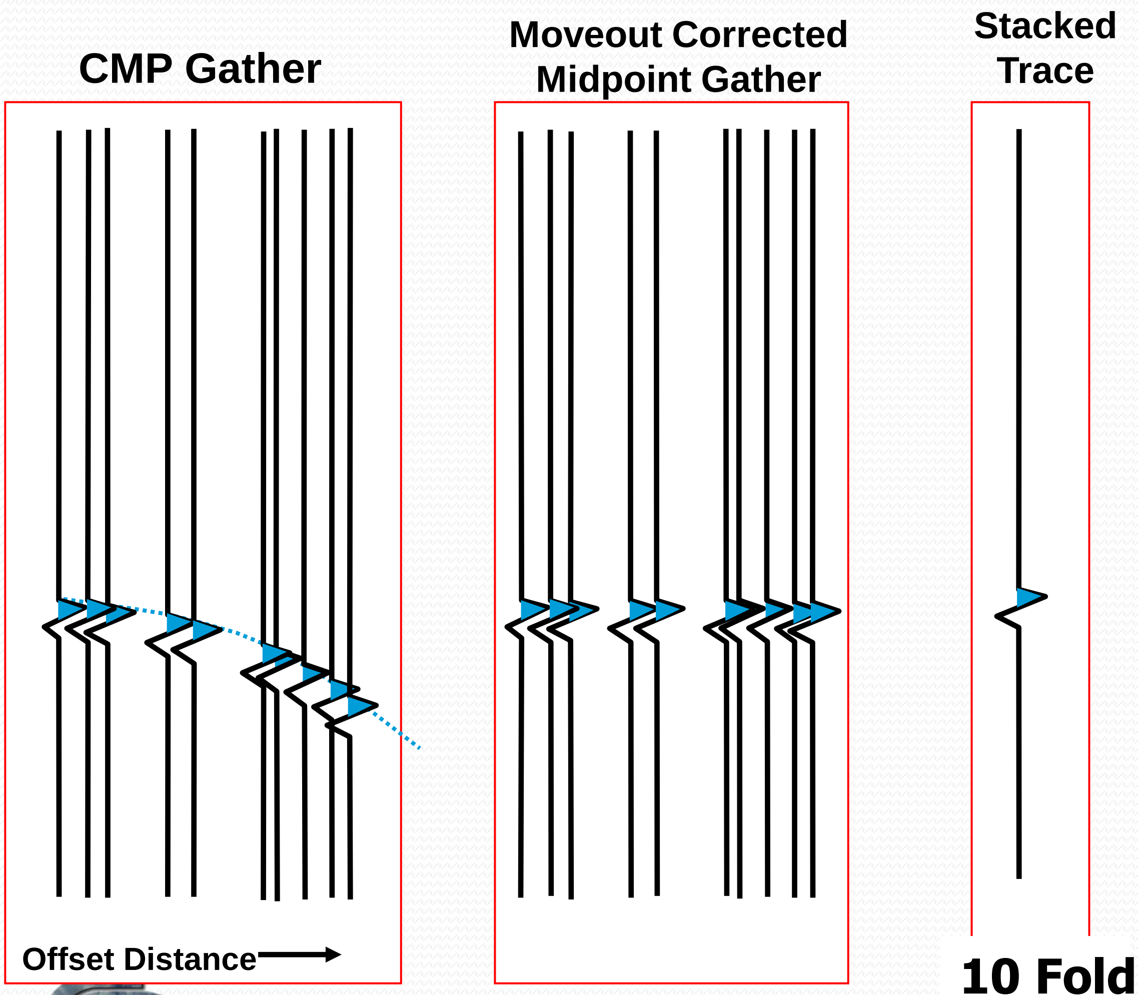
The travel times differ since the path for a near offset trace
is less than the path for a far offset trace

With the correct velocity, we can correct for the difference in travel time for each trace.

The curvature of this hyperbola is a function of the average velocity down to the depth of the reflection



Stacked Trace



Several offset traces are stacked (# traces = fold)

The geologic ‘signal’ will be additive

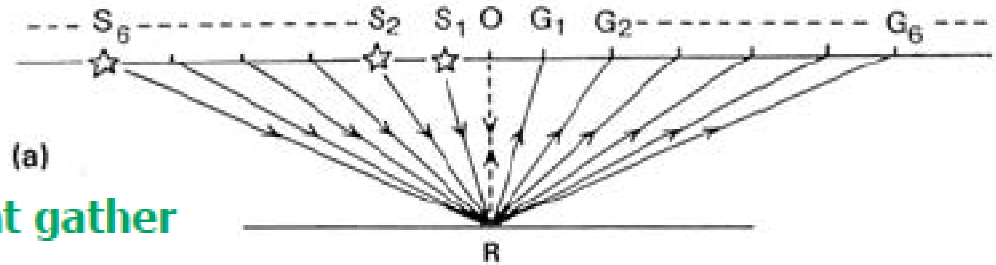
The random ‘noise’ will tend to cancel

Stacking greatly improves S/N (signal-to-noise)

Common midpoint gathers

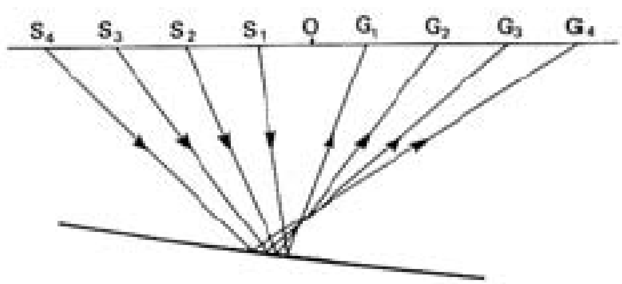
To enhance signal to noise we use more than one shot

Reflections from the same point are recorded by different source-station pairs



➔ **Common depth point gather**

For dipping layers the reflection points are "smeared"



➔ **Common midpoint gather**

Fig. 4.16 (a) Ray paths of reflections belonging to the common-depth point (CDP) which is located below the shot–geophone common midpoint, O. The arrangement shown gives a six-fold coverage of the subsurface reflection point, R, on a horizontal reflector. (b) For a dipping reflector, the reflection point is not vertically below the shot–geophone midpoint, O.

Static corrections

Correct for surface topography and the weathered surface layer

Surface topography

Time correction to each trace:

$$t_g = (E_g - E_d)/V$$

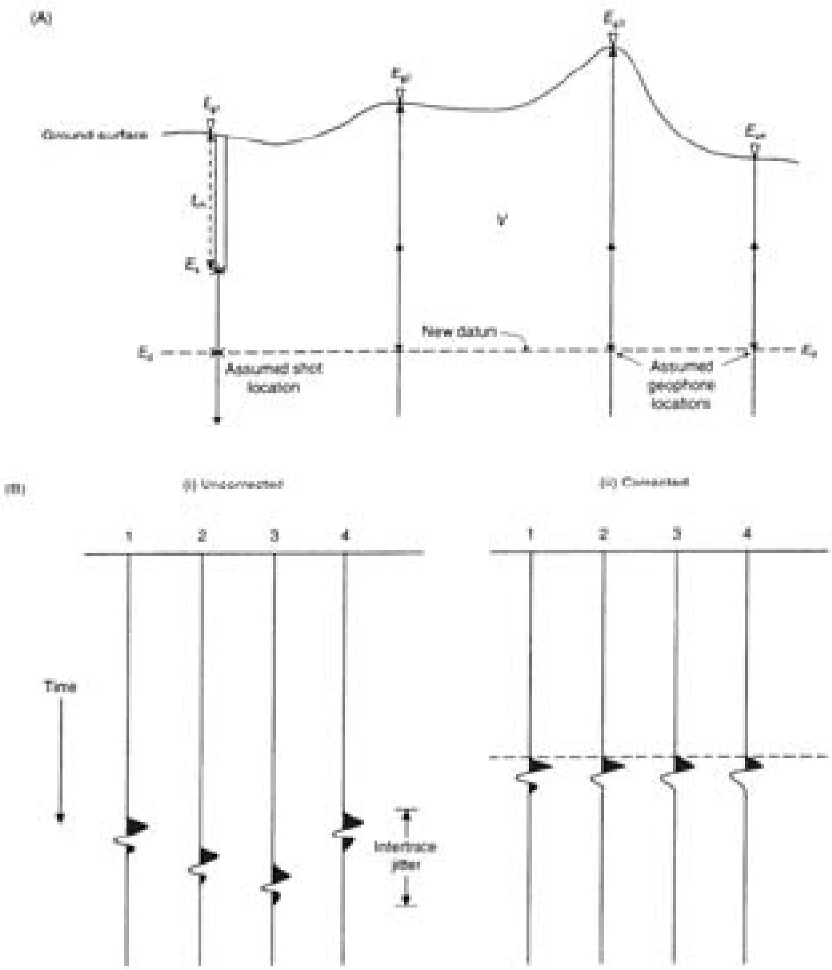
Source depth

$$t_s = (E_s - E_d)/V$$

total correction

$$t_e = t_s + t_g$$

Shift each trace by this amount to line up deeper reflectors



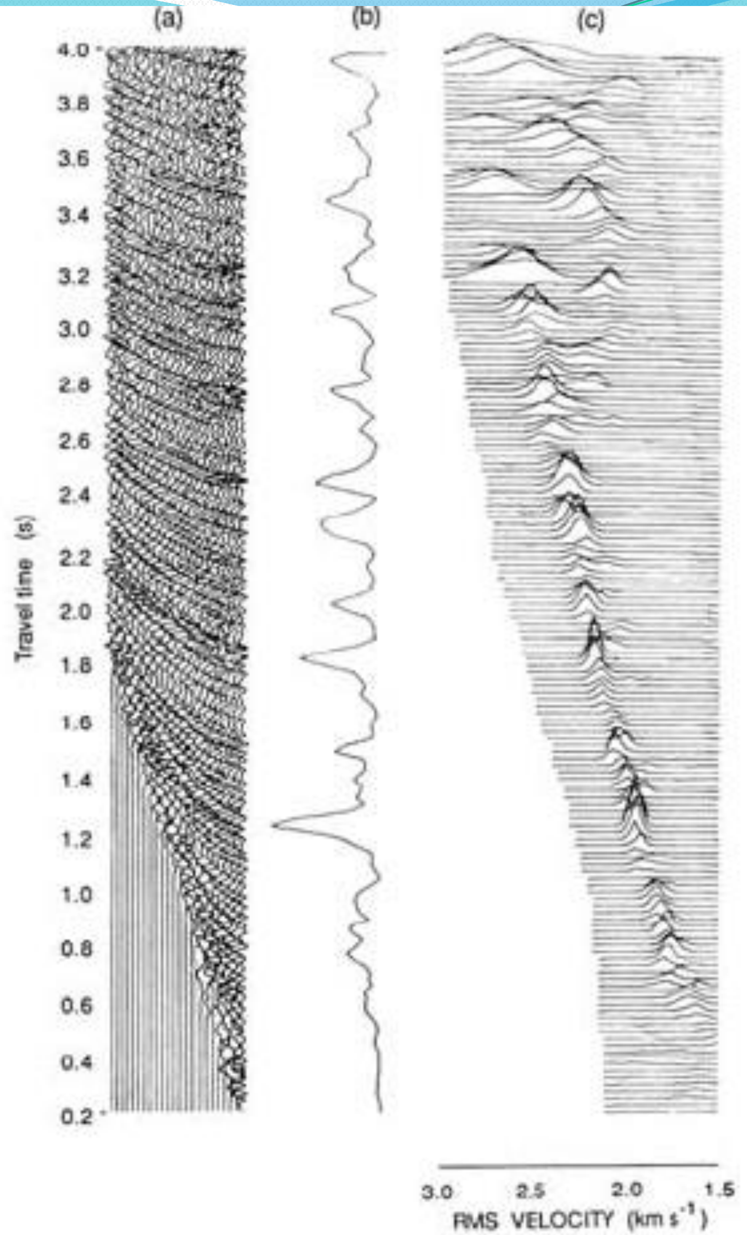
Velocity analysis

Determination of seismic velocity is key to seismic methods

Velocity is needed to convert the time-sections into depth-sections i.e. geological cross-sections

Unfortunately reflection surveys are not very sensitive to velocity

Often complimentary refraction surveys are conducted to provide better estimates of velocity



Normal move out (NMO) correction

The reflection traveltime equation predicts a hyperbolic shape to reflections in a CMP gather. The hyperbolae become fatter/flatter with increasing velocity

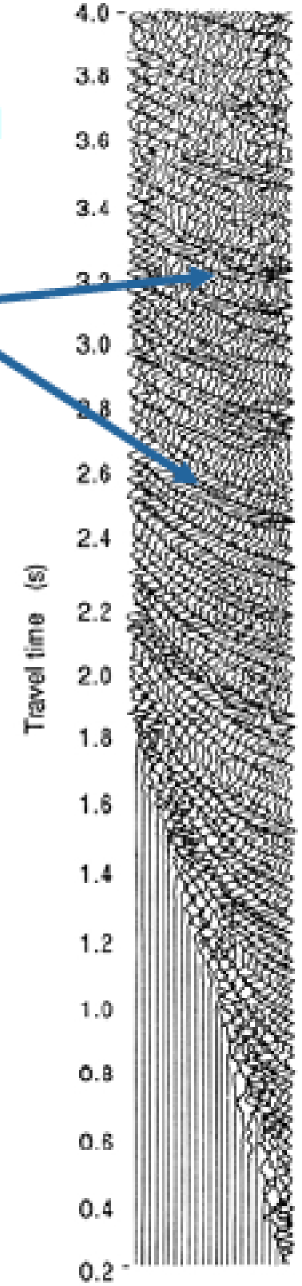
$$T_x^2 = T_0^2 + \frac{x^2}{V_1}$$

We want to subtract the NMO correction from the common depth point gather

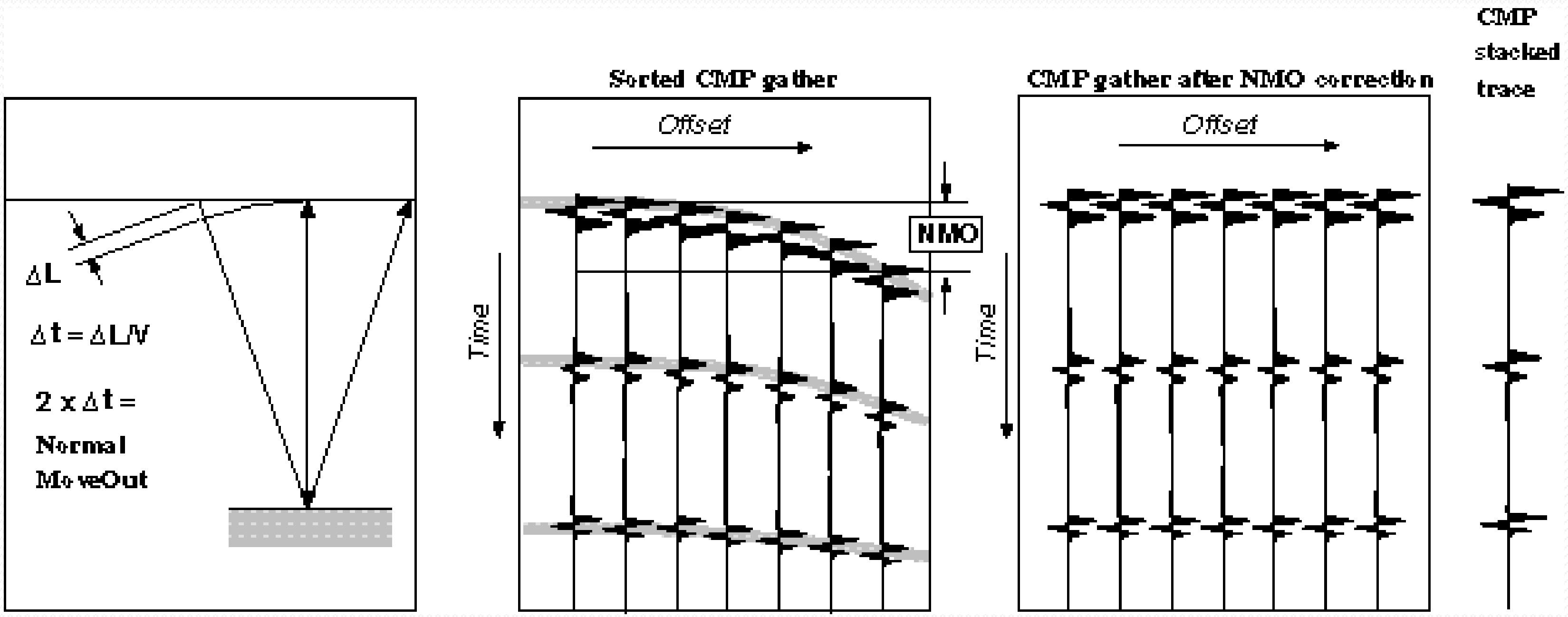
$$\Delta T_{NMO} \approx \frac{x^2}{2T_0V_1^2}$$

But for that we need velocity…

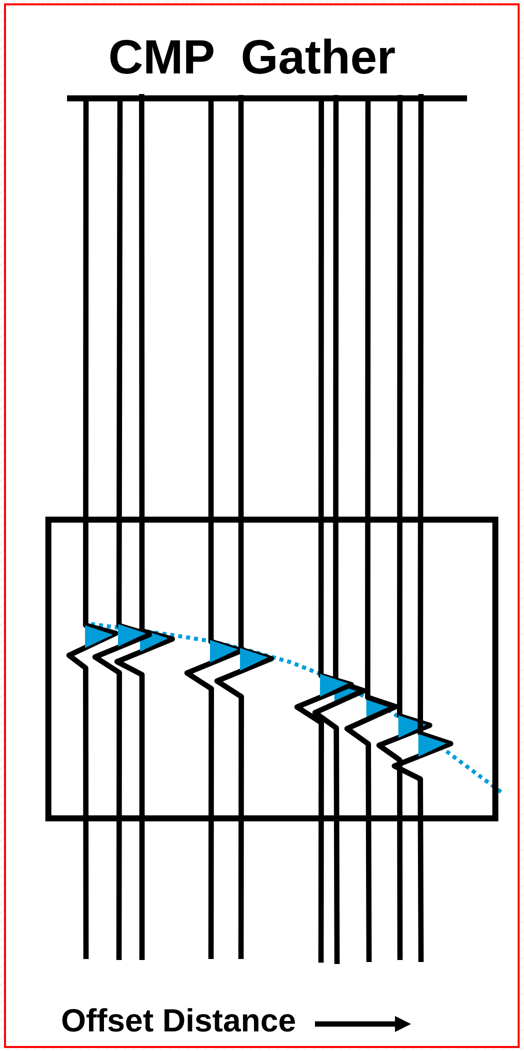
reflection hyperbolae become fatter with depth (i.e. velocity)

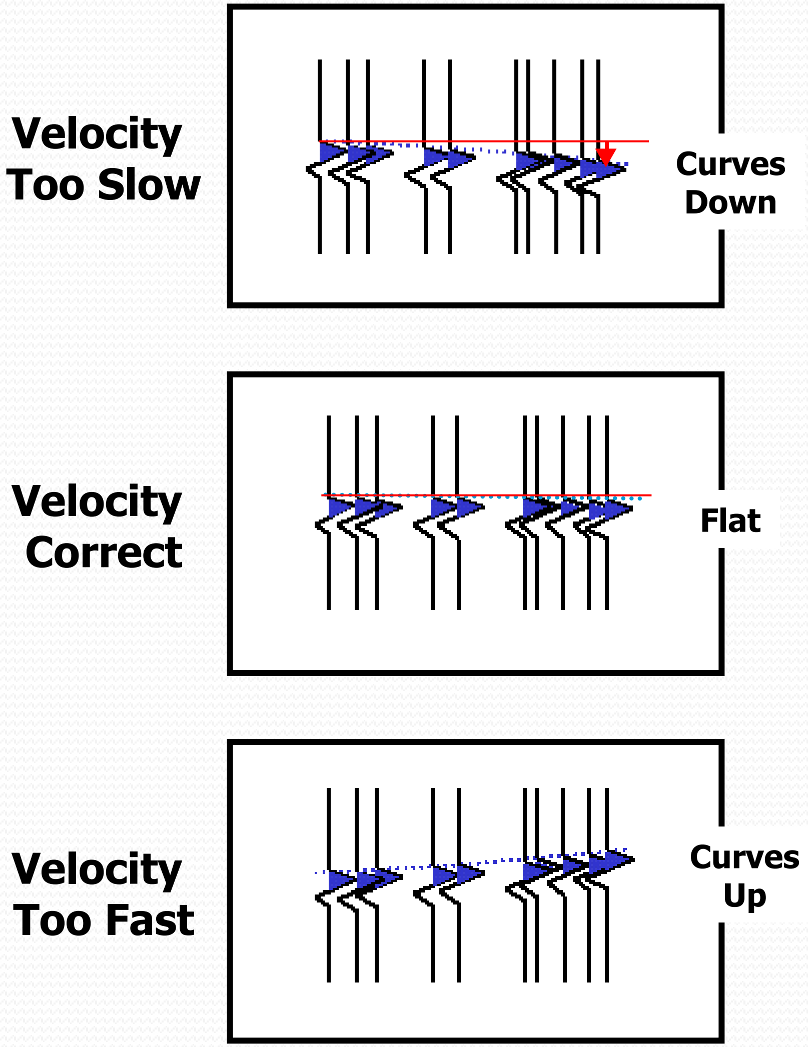


Normal Move Out correction is the process to cancel the travel time delay caused by the geometry of reflection with the estimated velocity. On the offset and time chart, the reflection signal from the same reflector will be align horizontal. After the NMO correction the every traces of the CMP gather may simply be summed and result a noise reduced trace (CMP stack).



With Correct Velocity, Gather is Flat





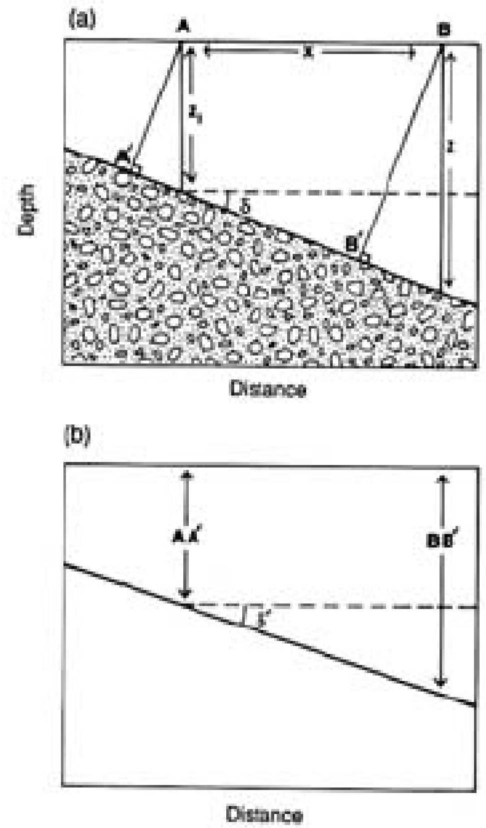
Dipping layers

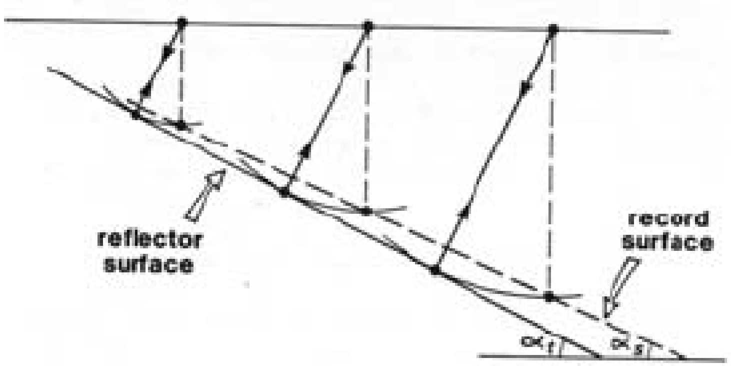
For horizontal reflectors the reflection point is vertically below the source/receiver

For dipping layers the reflection comes from a point up dip

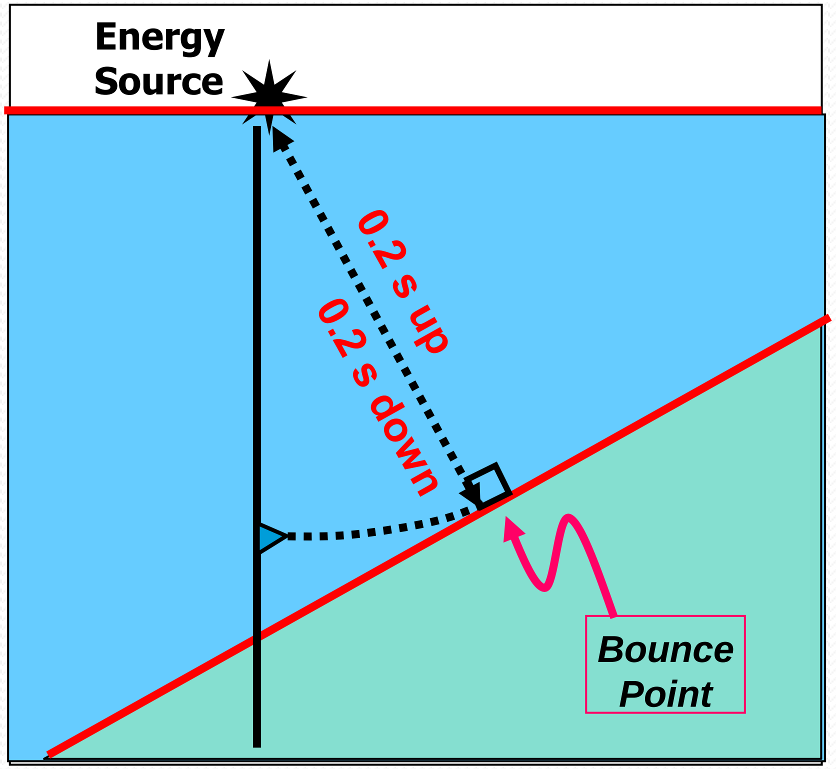
Therefore, a traveltime section will always show a reduced dip

$$\tan \delta' = \sin \delta$$

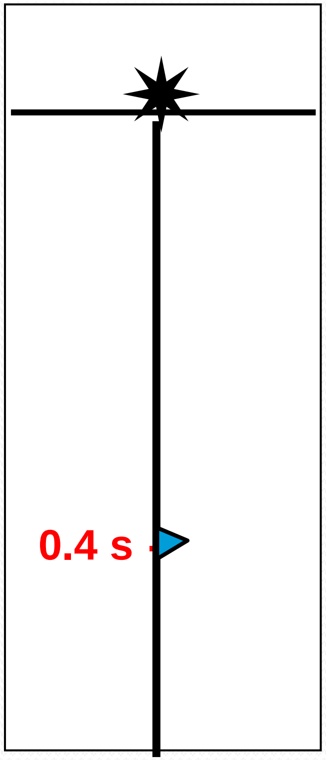




Positioning Problems



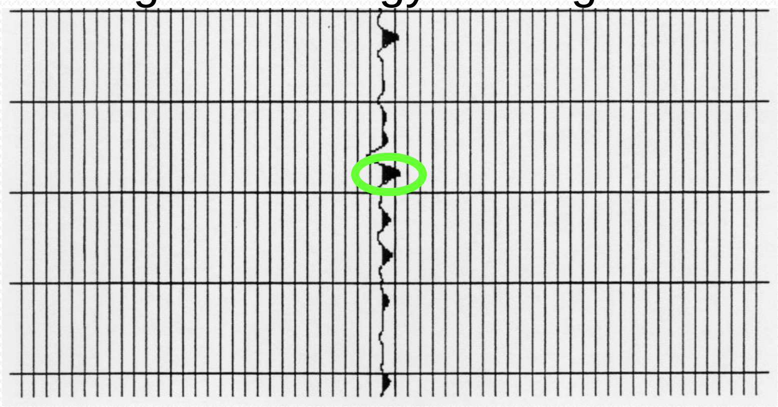
The seismic ray hits an inclined surface at 90º and reflects back



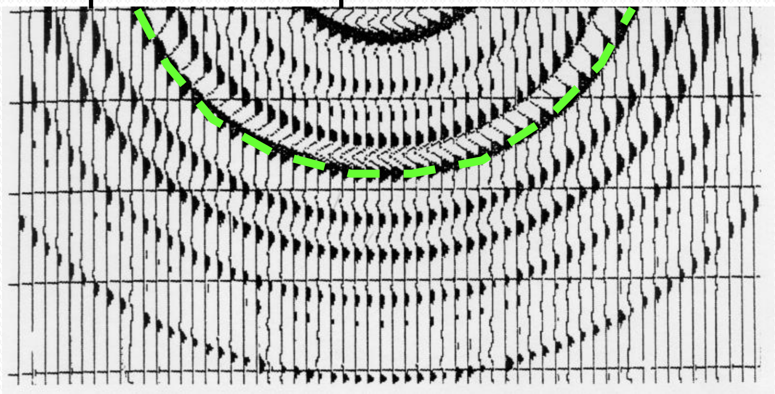
The reflection is displayed beneath the source-receiver midpoint

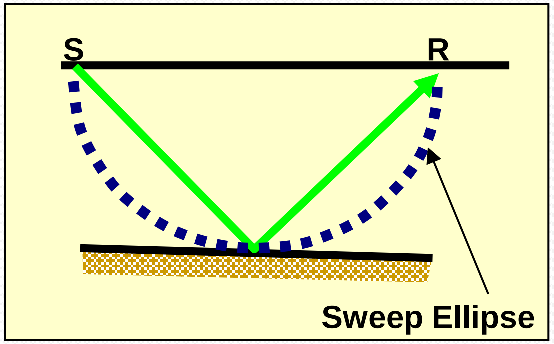
Migration – Correcting for Location

Unmigrated energy on single trace...

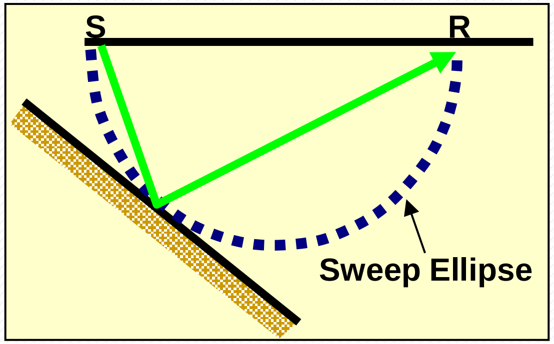


...spread to all possible locations of origin

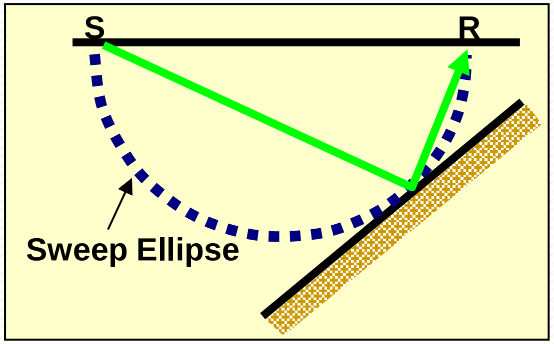




OR



OR



Migration

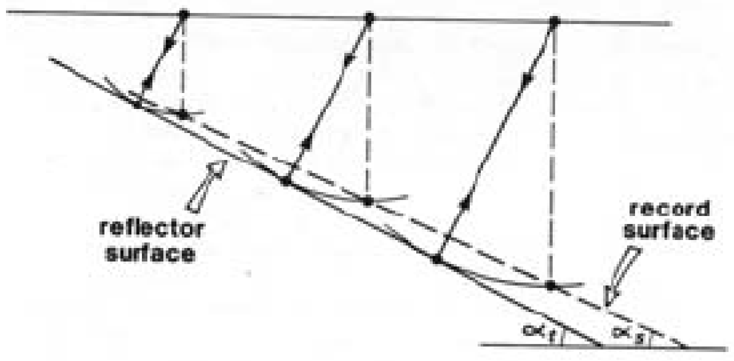
The process of trying to move reflections back to their point of origin

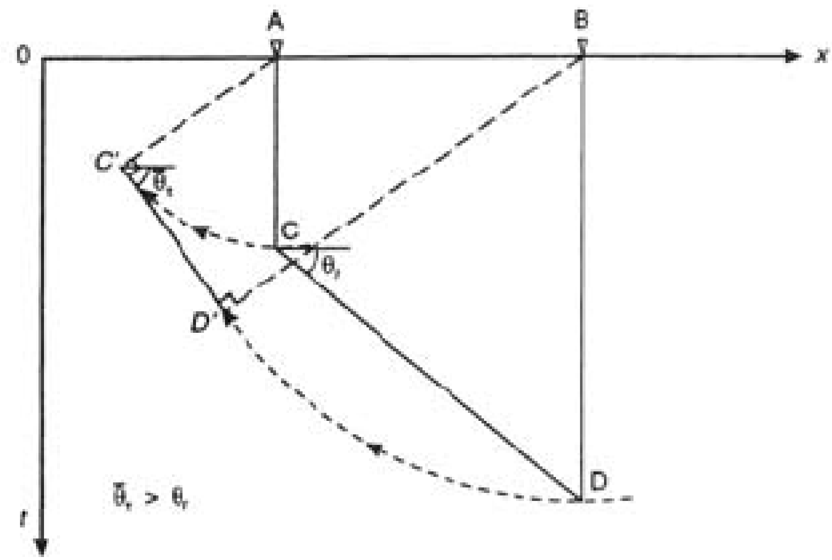
Intended to deal with

- Dipping interfaces
- Curved interfaces
- Diffractions
- Reflections from the 3rd dimension

Time migration: restore the geometrical relationships between seismic events on the time section

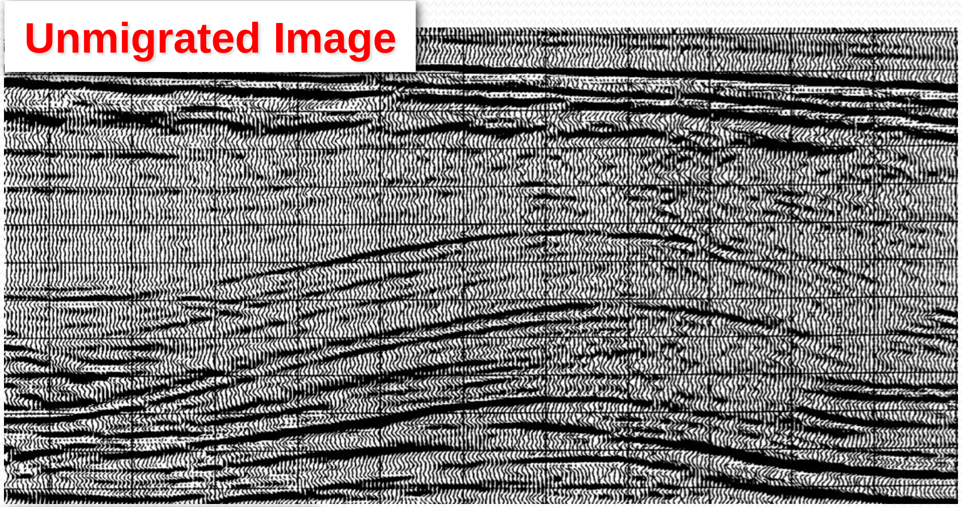
Depth migration: generates a true depth section. Necessary when strong lateral velocity gradients



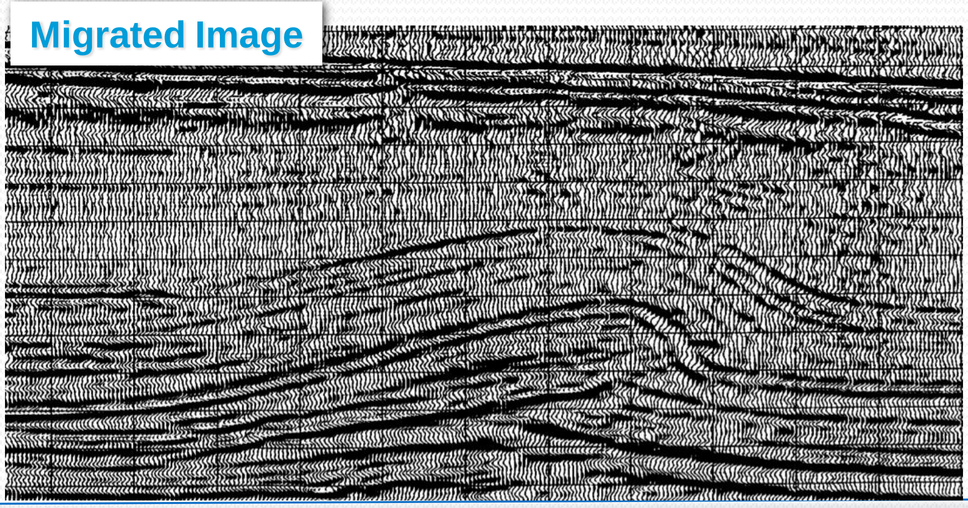


Seismic Migration

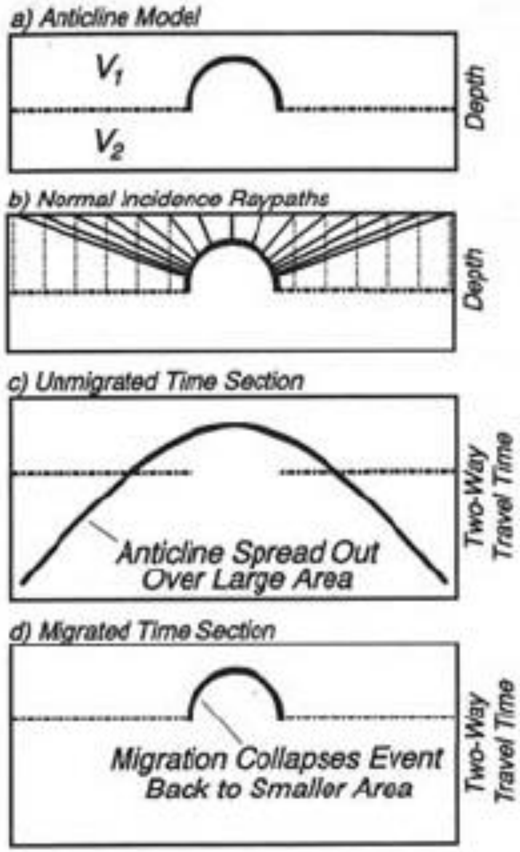
Positioning Problems
'Blur' the Image

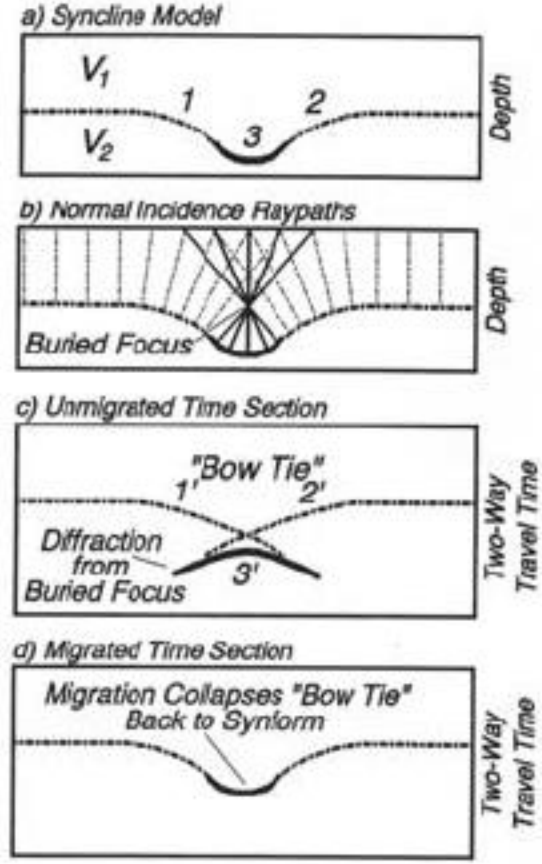


Migration Reduces Positioning Problems, which Improves the Image



Anticlines and synclines

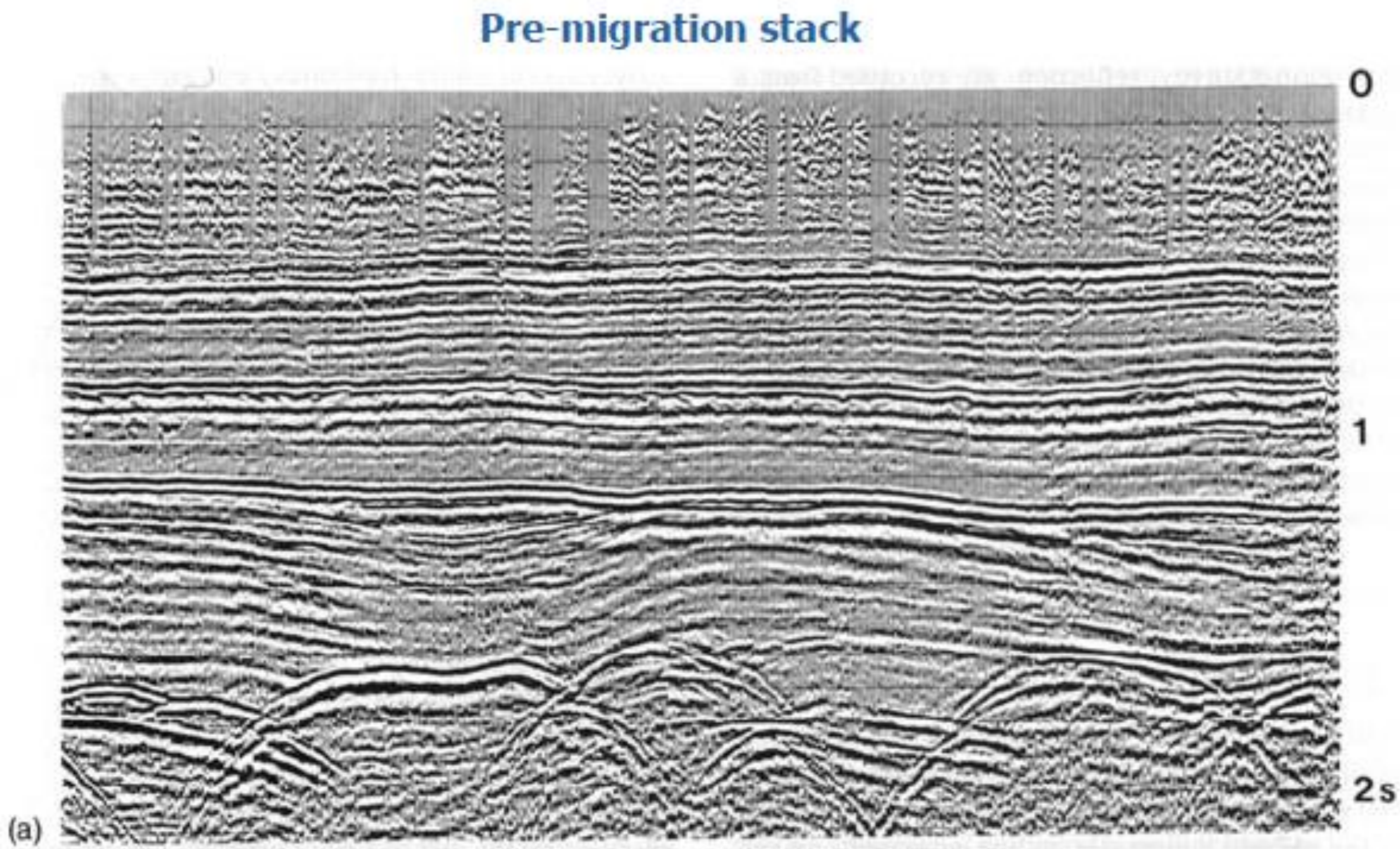




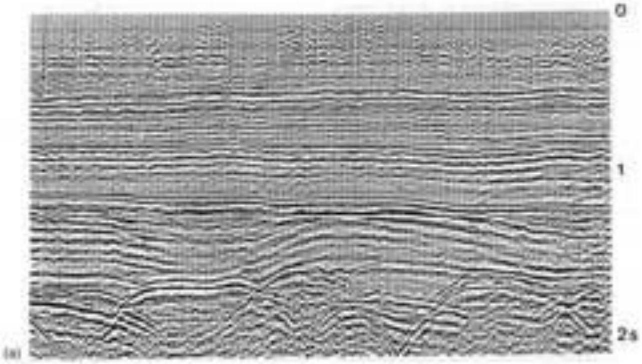
Anticlines broaden

Synclines produce a bow-tie

Anticlines and synclines

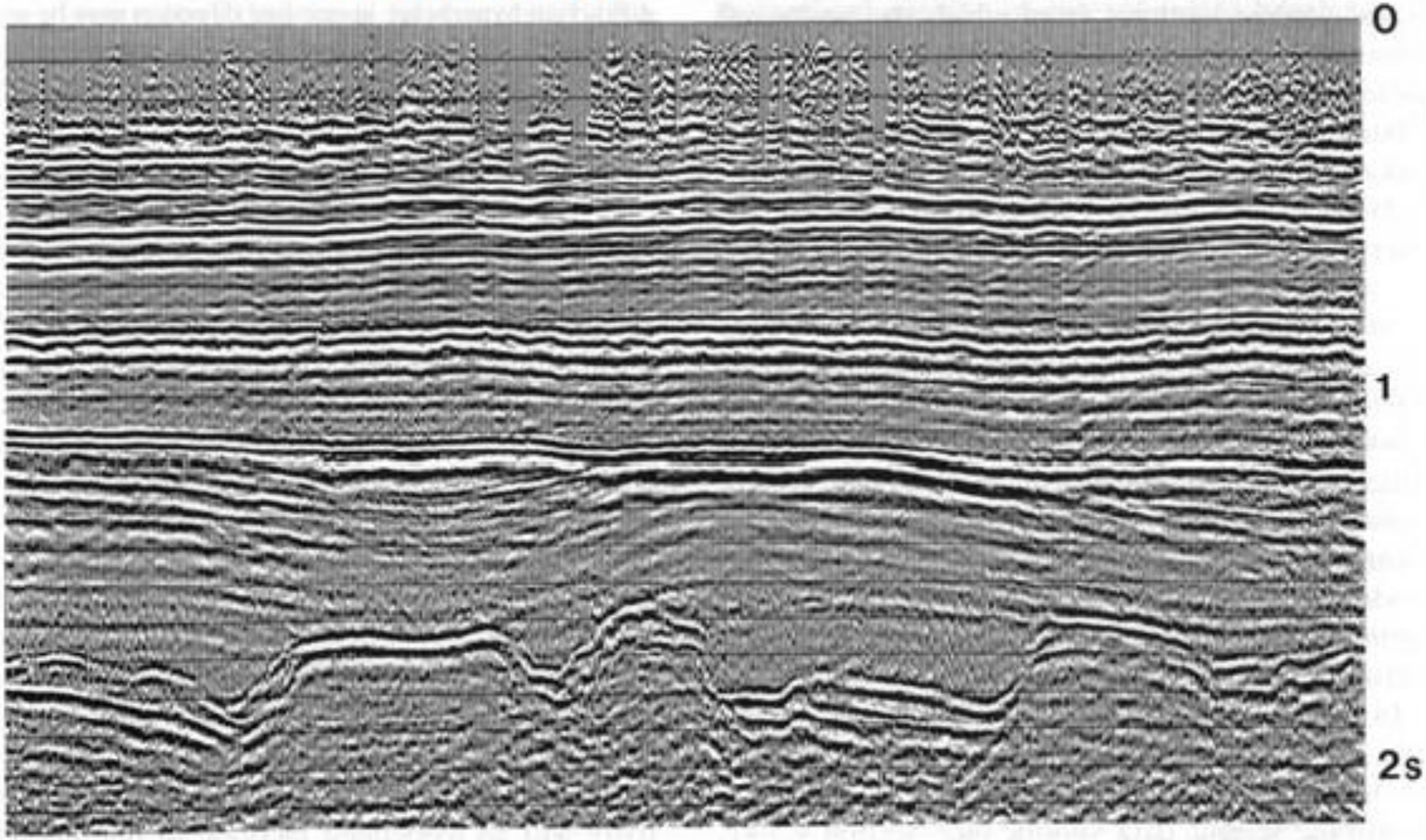


Anticlines and synclines



(a)

Migrated stack



(b)

Velocity distortions:

Fault distortions

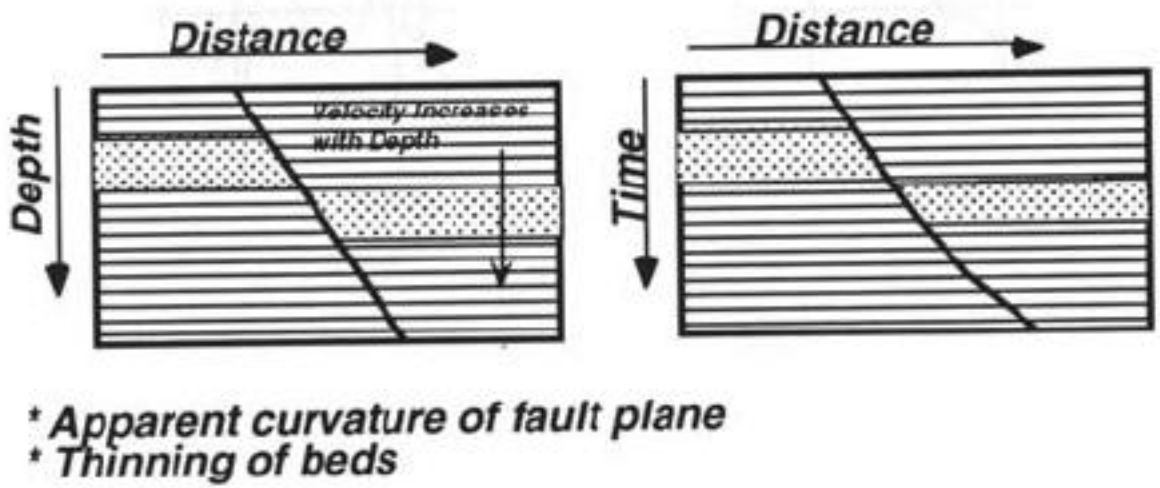
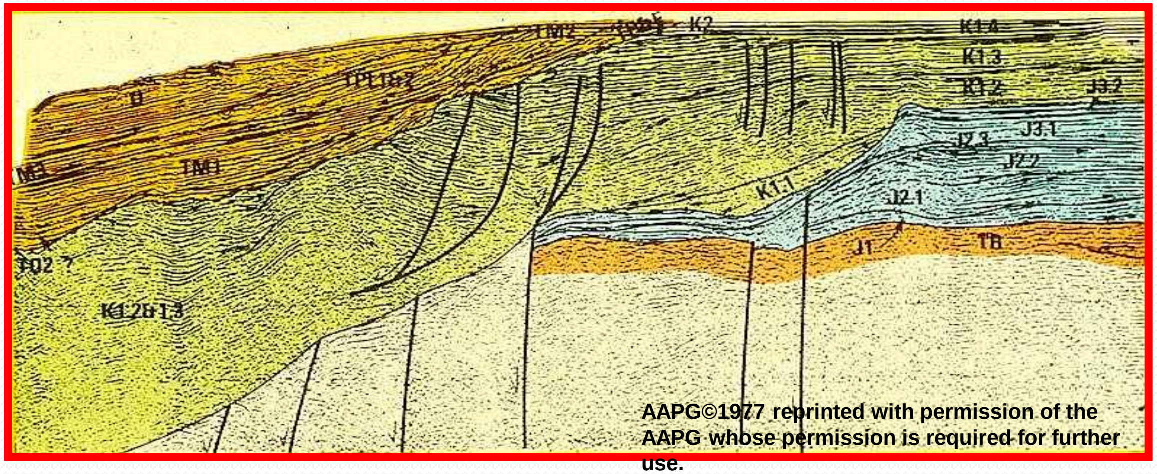


Figure 4.9. Ambiguities remain when using seismic data to map and interpret structural features. Since velocities are variable with depth, distortion of fault planes and bed thickness due to velocity effects is a possibility. This example shows a case where velocities increase with depth (the usual situation).

Seismic Interpretation

Mitchum et al., 1977



Determine the local geology from the subsurface images

- Map faults and other structural features
- Map unconformities and other major stratal surfaces
- Interpret depositional environments of sediments
- Infer lithofacies from reflection patterns & velocities
- Predict fluid flow and saturation

Examples

Delineating bedrock

Why would we want to know this?

Correlating seismic with well log data

- Drilling a well provides "ground truth" to a seismic interpretation
- Borehole provides velocities for depth migration
- Synthetic seismograms generated from the well log can be tied to the seismic

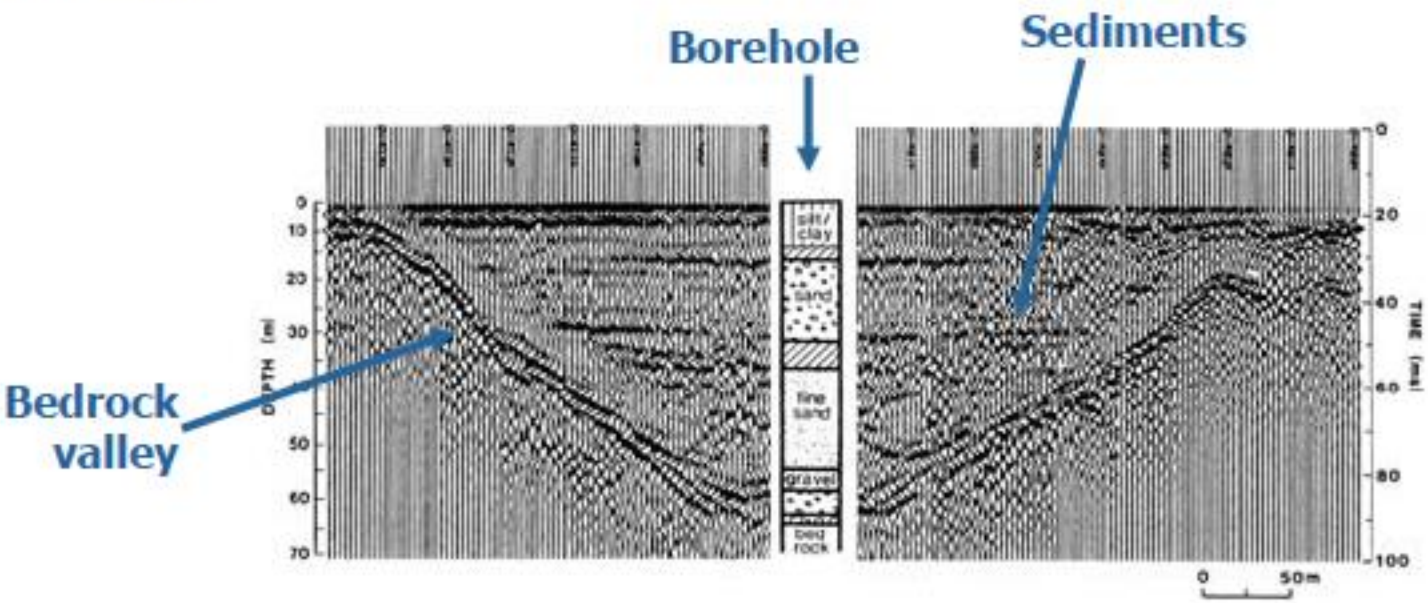


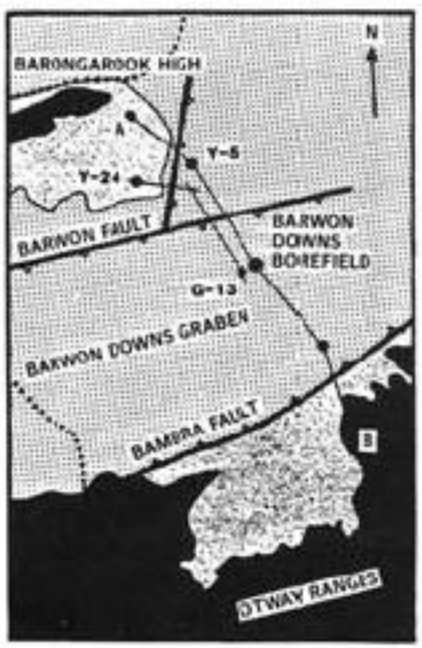
Fig. 4.30 Optimum common offset (COF) reflection section and the borehole log from Dryden, Ontario, Canada, showing a steep-sided bedrock valley. 100 Hz geophone used with an offset of 15 m. (After Pullan and Hunter, 1990.)

Examples

Groundwater

Objective:

Map subsurface location of aquifer for the purpose of drilling a well



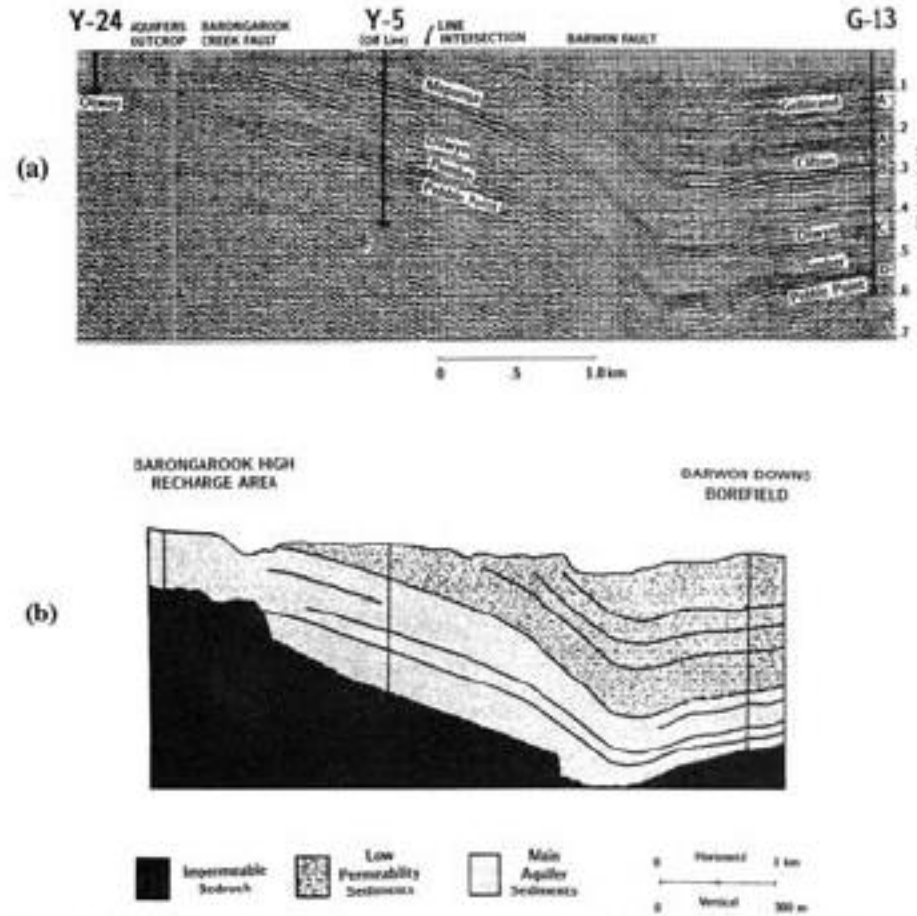


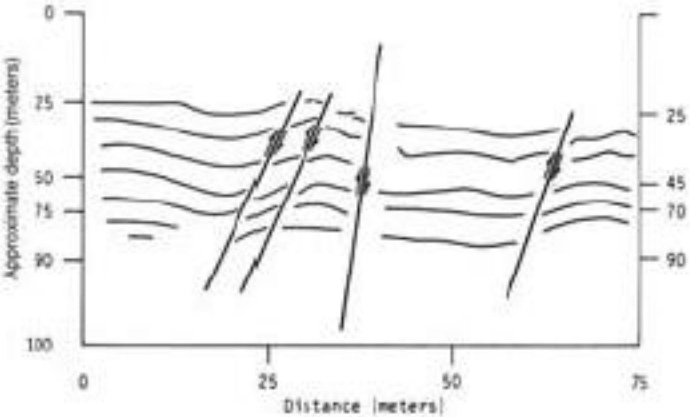
Fig. 4.29 (a) Seismic section below the survey line Y-24–G-13 (see location map, Fig. 4.28). Amplitude normalization and 3×vertical exaggeration used to emphasize structure in this section across the Barwon Downs graben. Main aquifer units are named below the line intersection; boreholes shown by thick solid lines. (b) Yeodene survey hydrogeological interpretation. The basal Tertiary aquifer system, confined between a calcareous aquitard cap and impermeable bedrock, is shown to be continuous between the Barongarook recharge area and the Barwon Downs extraction area. (After Geissler, 1989.)

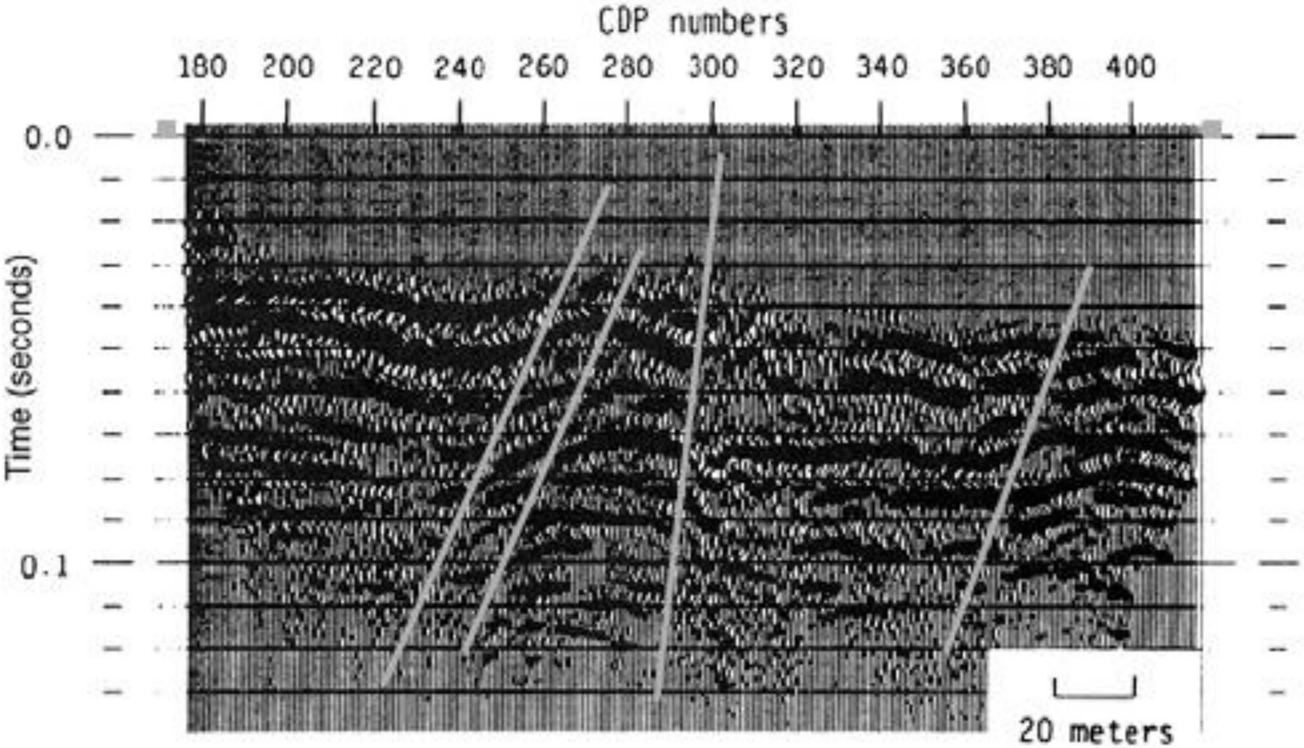
Examples

Locating faults

- ➔ **Migrating fluids**
- ➔ **Seismic hazard**

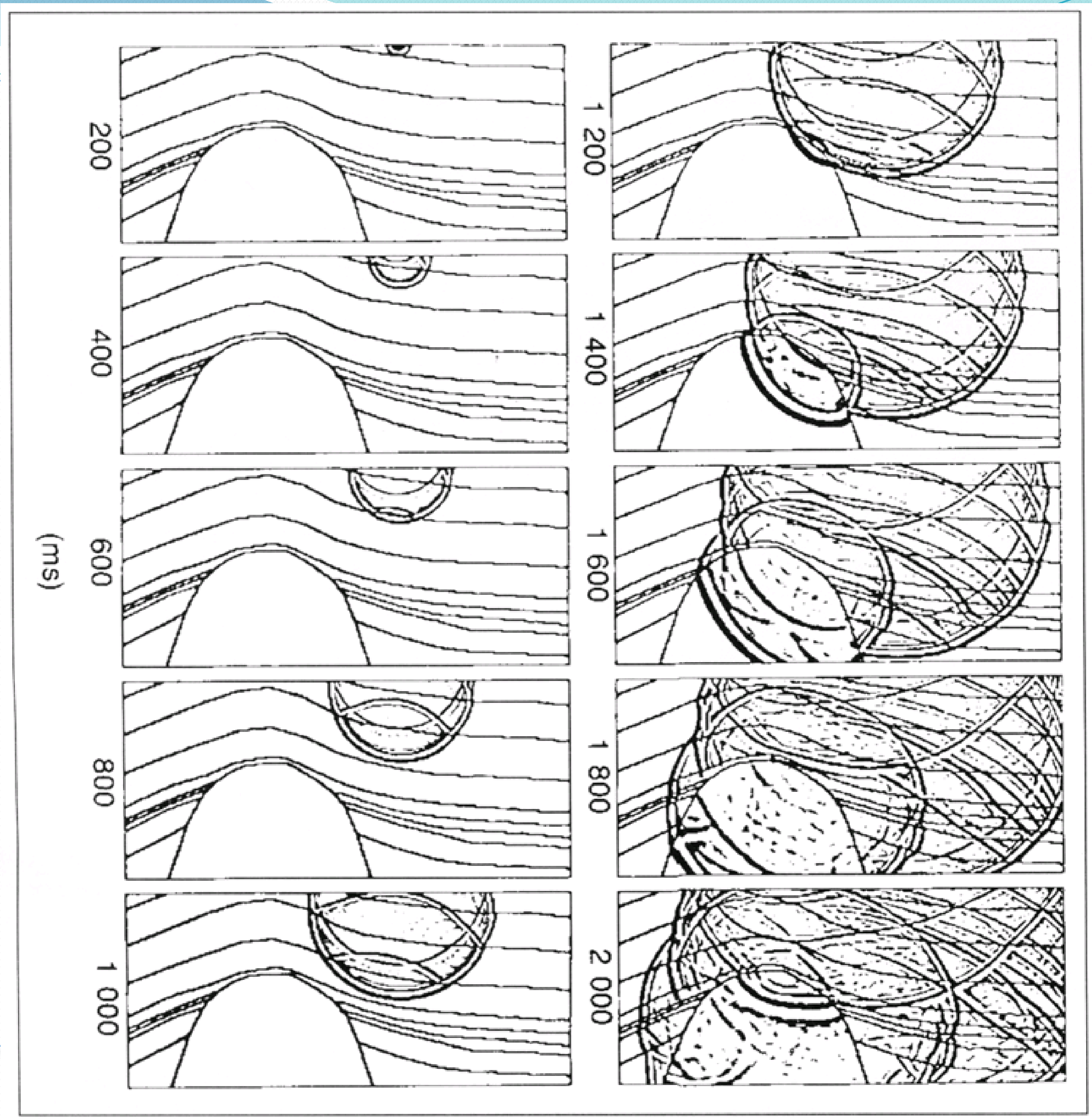
Identified as discontinuities in reflection surfaces





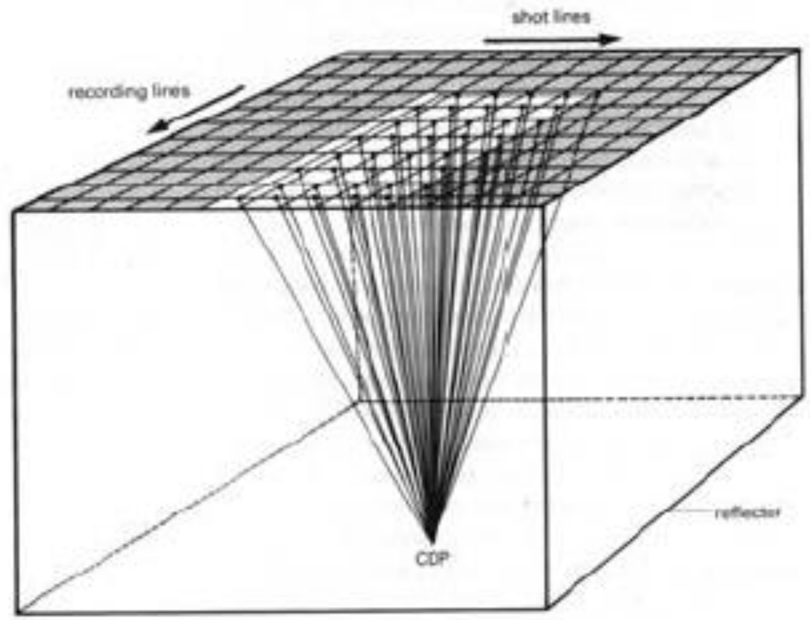
None of these faults visible at the surface – suggests recent inactivity

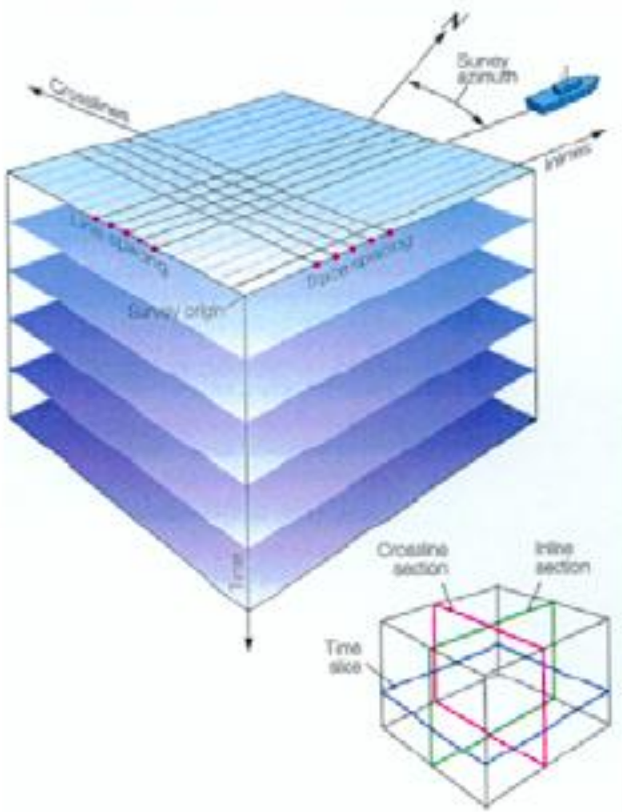
Seismic wavefield snaphots (simplified salt dome model)



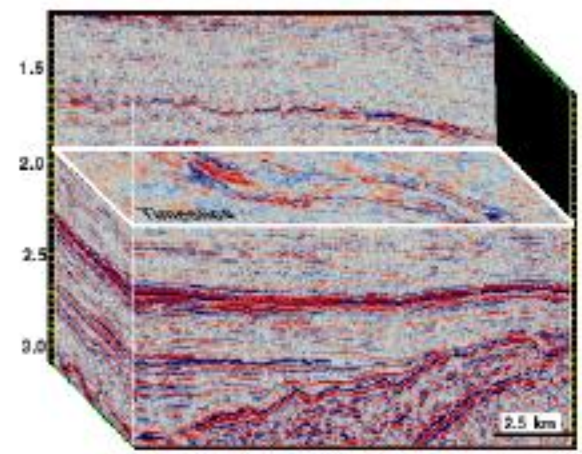
3D surveys

Collect data on a grid rather than along a line





Produces a data cube rather than a line

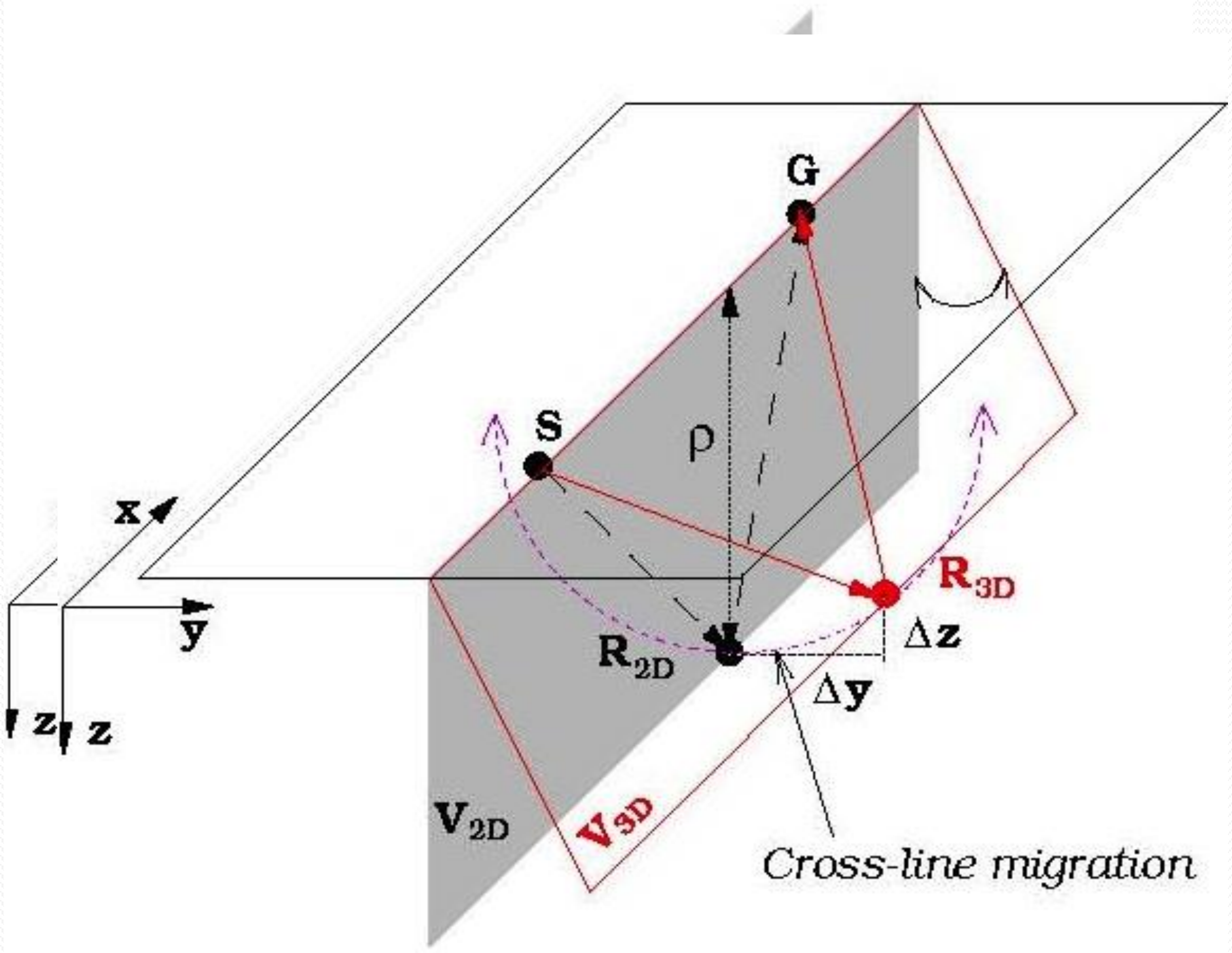


The development of 3D seismic is particularly effective in geothermal exploration, since goethermal areas are characterized by high heterogeneity in the form of fractures or matrix complexity. The complex target complicates the seismic sections, producing severe scattering and attenuation, and therefore many “no record” sections.
Before 3D, the general conclusion was that surface reflection was not as useful or routine as in the gas and oil sector.

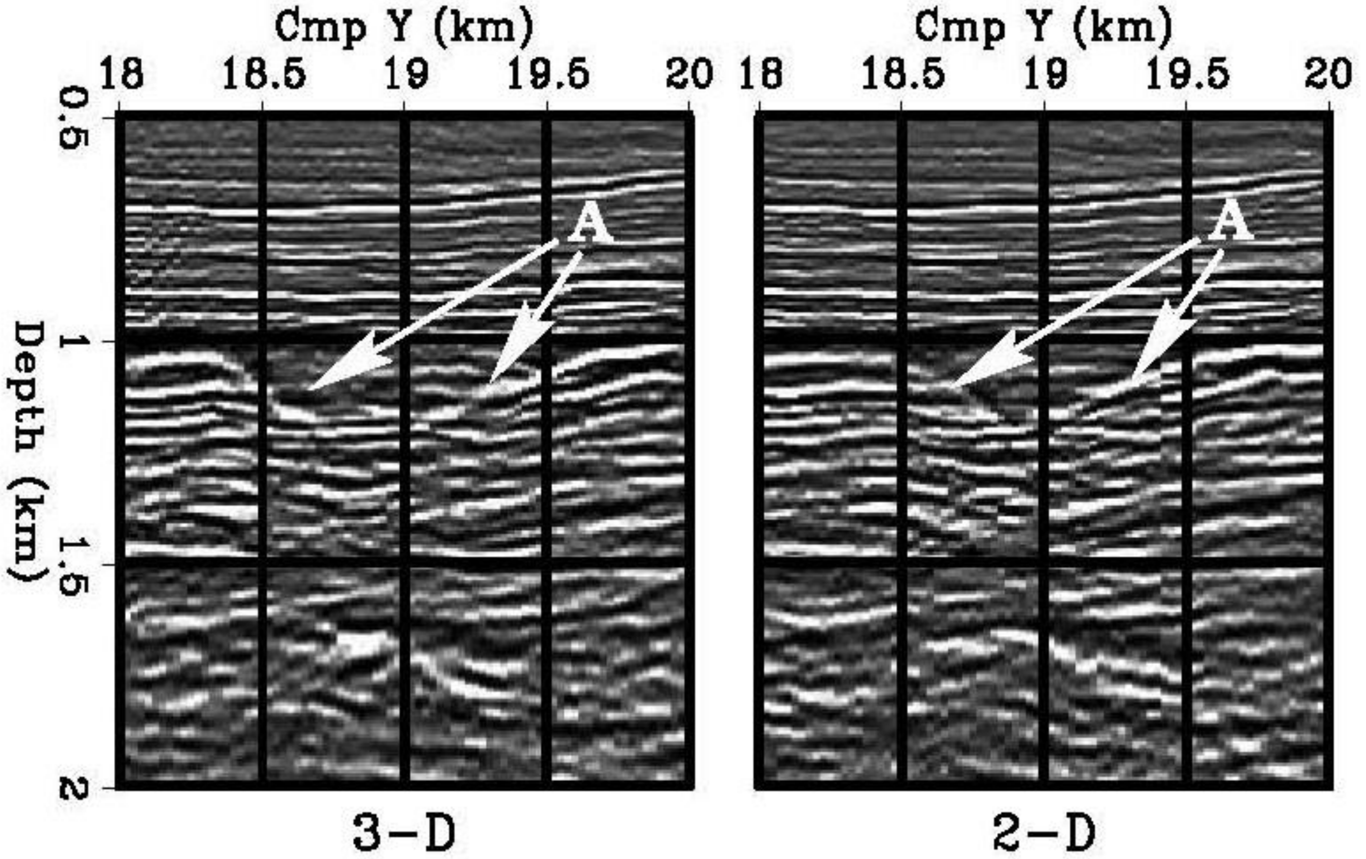
This conclusion is not valid nowadays, and very interesting results are now avaialble also in the geothermal comunity.

What remains, however, is the high cost of 3D seismic, as compared to geothermal revenues.

Geometric reasoning in 3-D

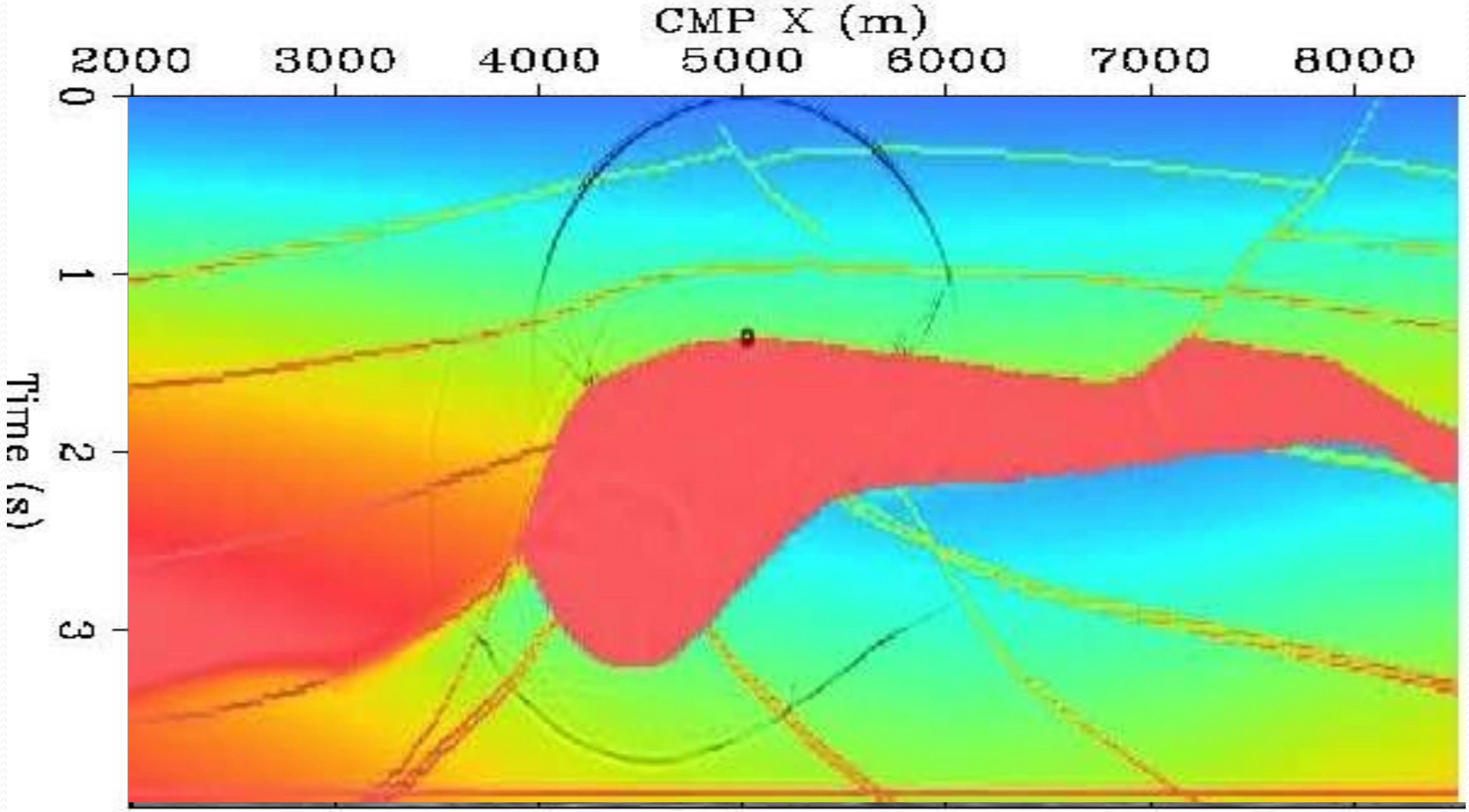


2-D imaging of a 3-D world: pitfalls and errors



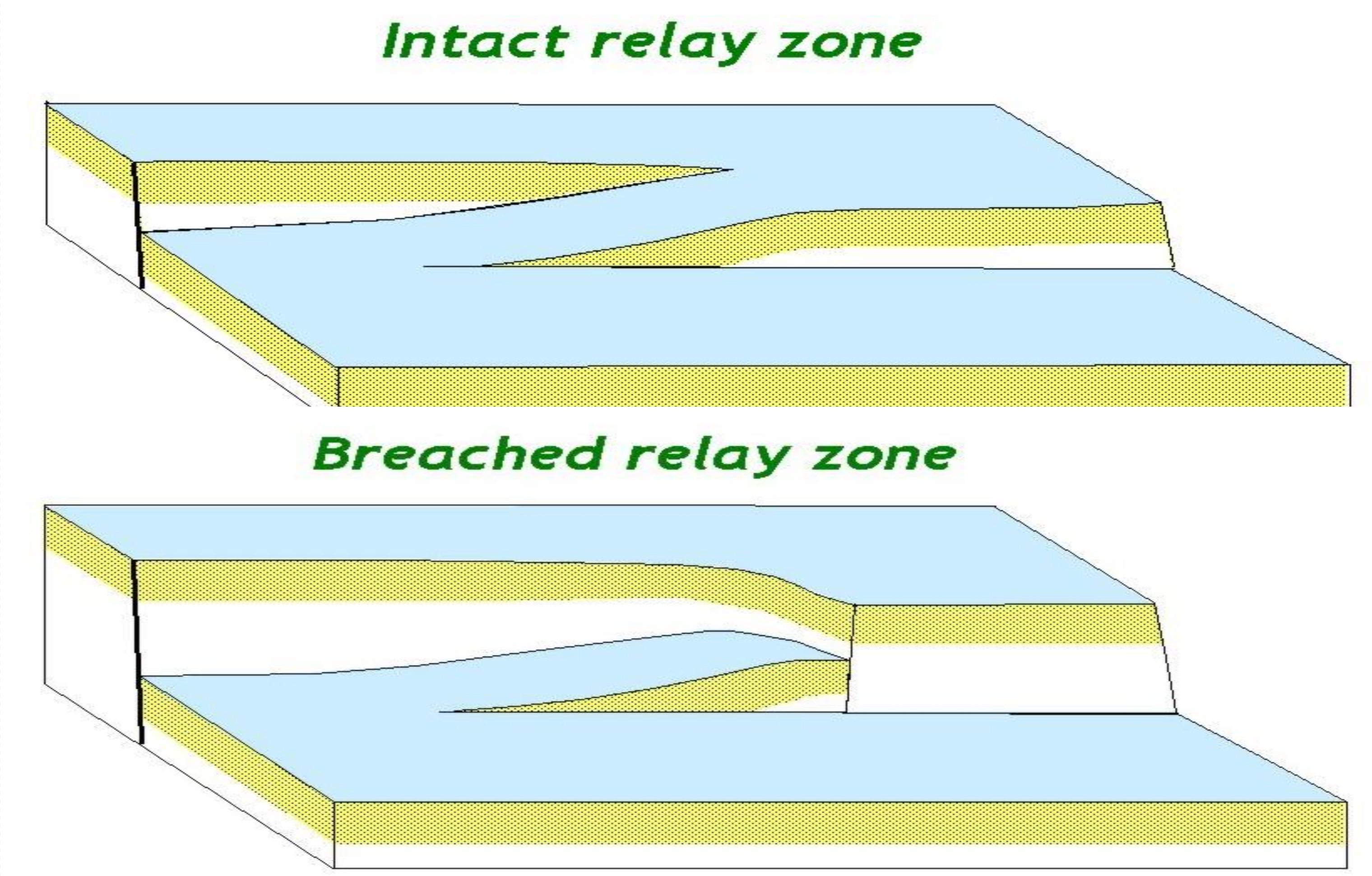
Dipping reflectors: mispositioning in 2-D

Structural model enhancement from 3-D imaging

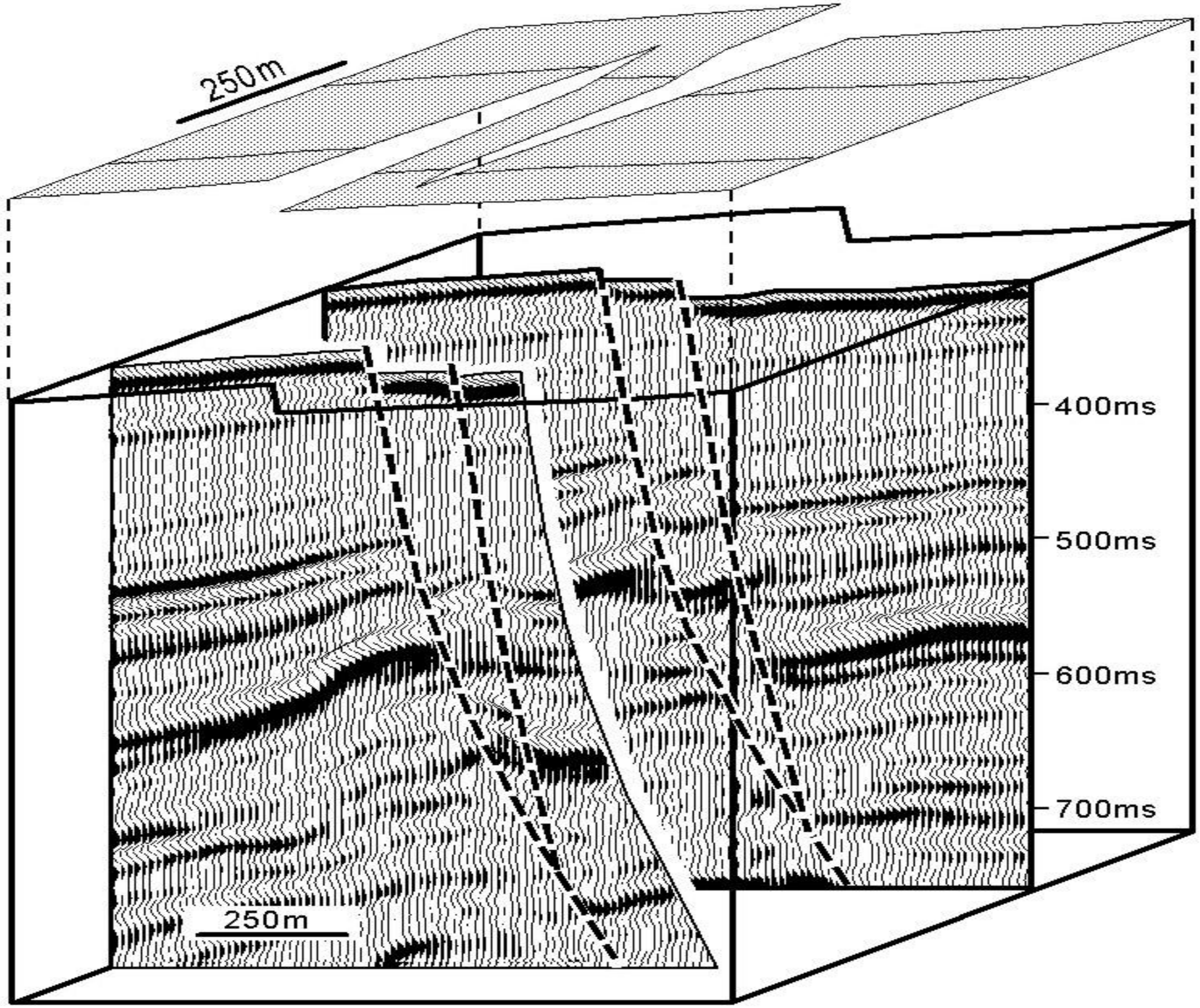


Strained and fractured Earth: the ground truth…

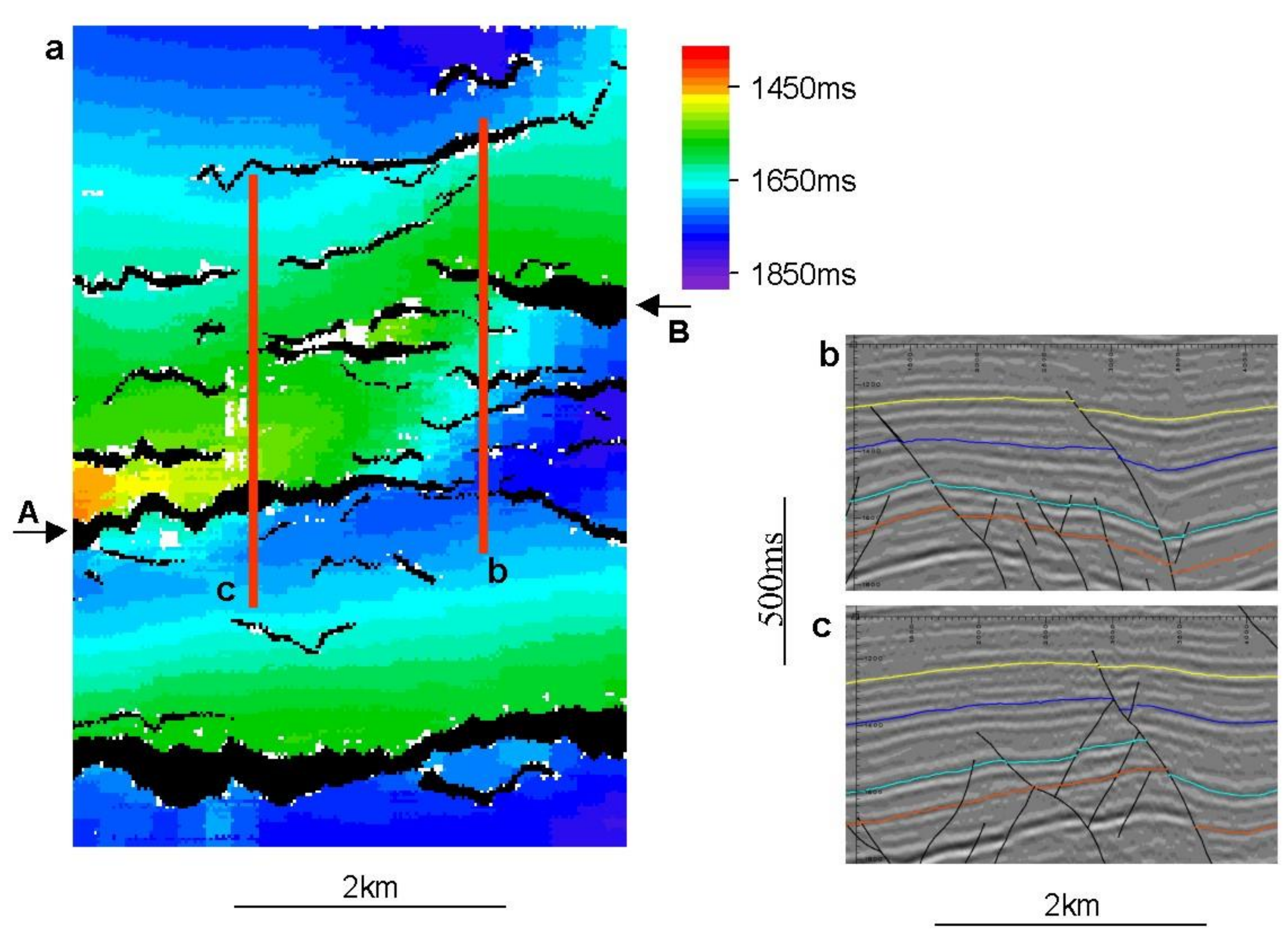
… the subsurface model…



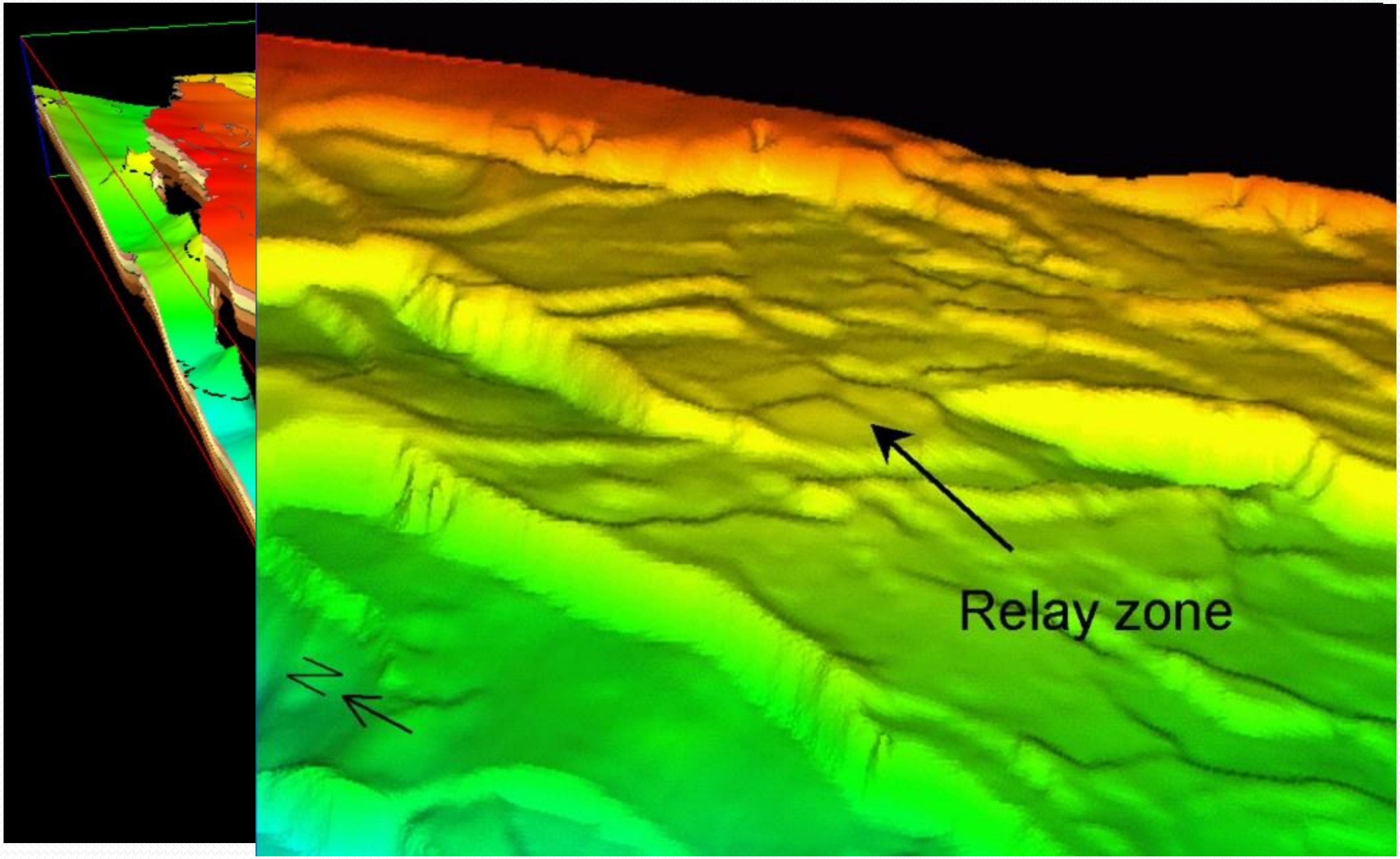
…the seismic image…



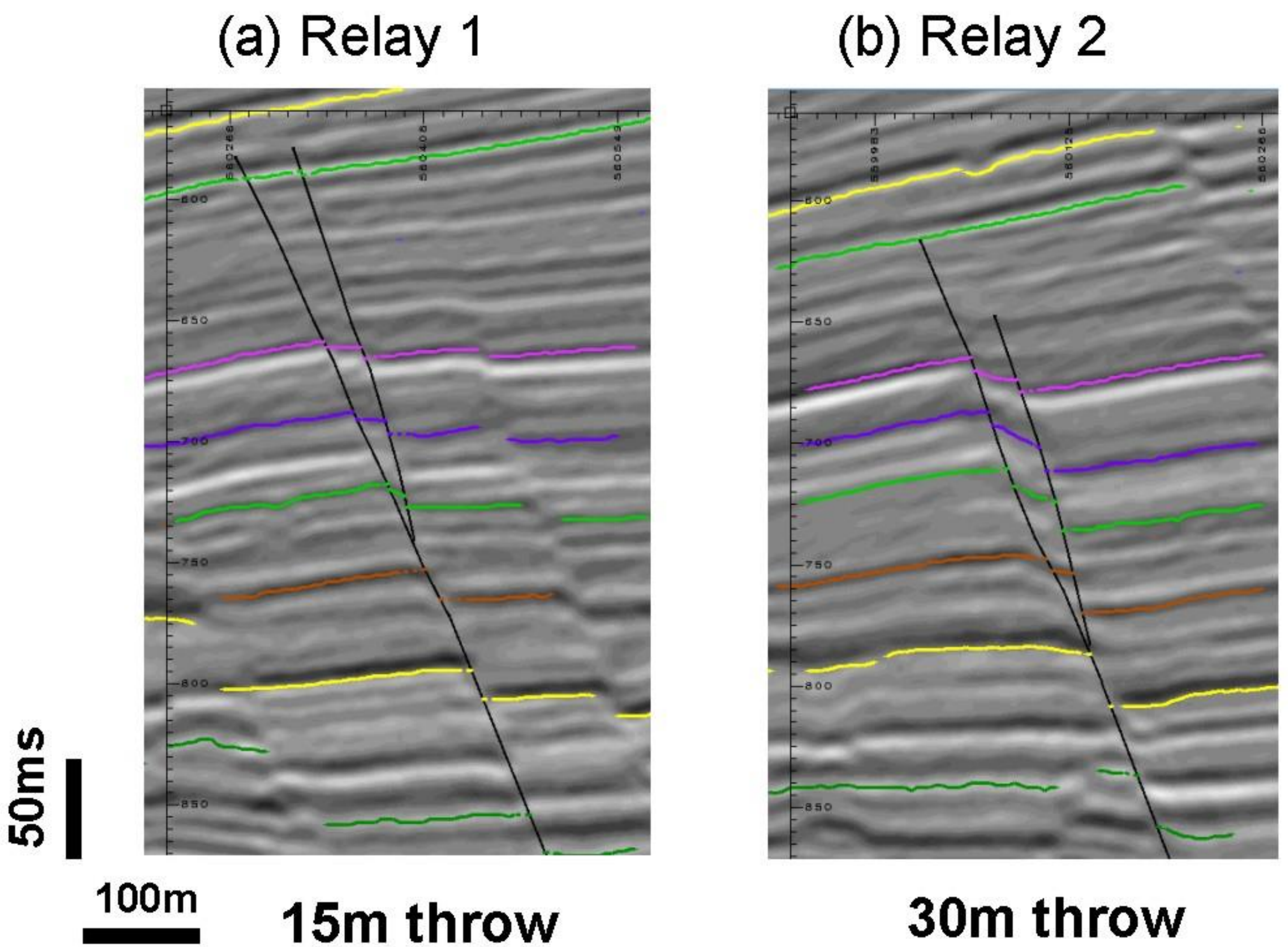
3-D seismic study of a strained and fractured Earth..



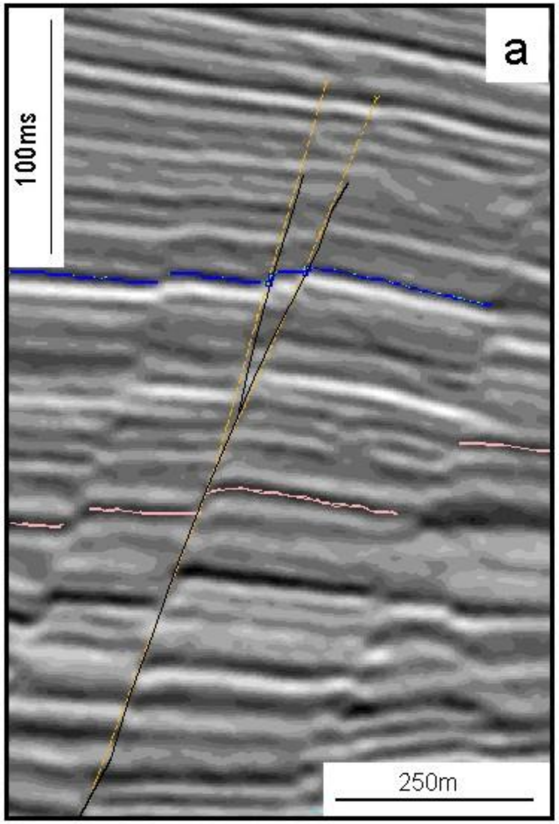
…at regional scale

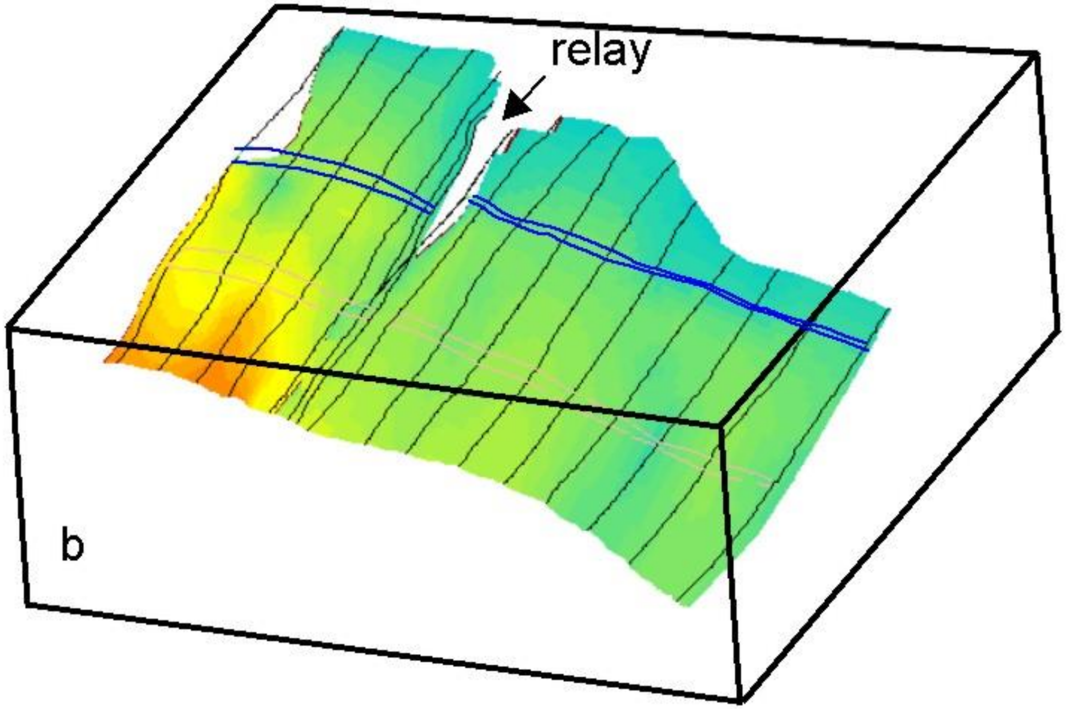


Resolving power in 3-D cross-sections..



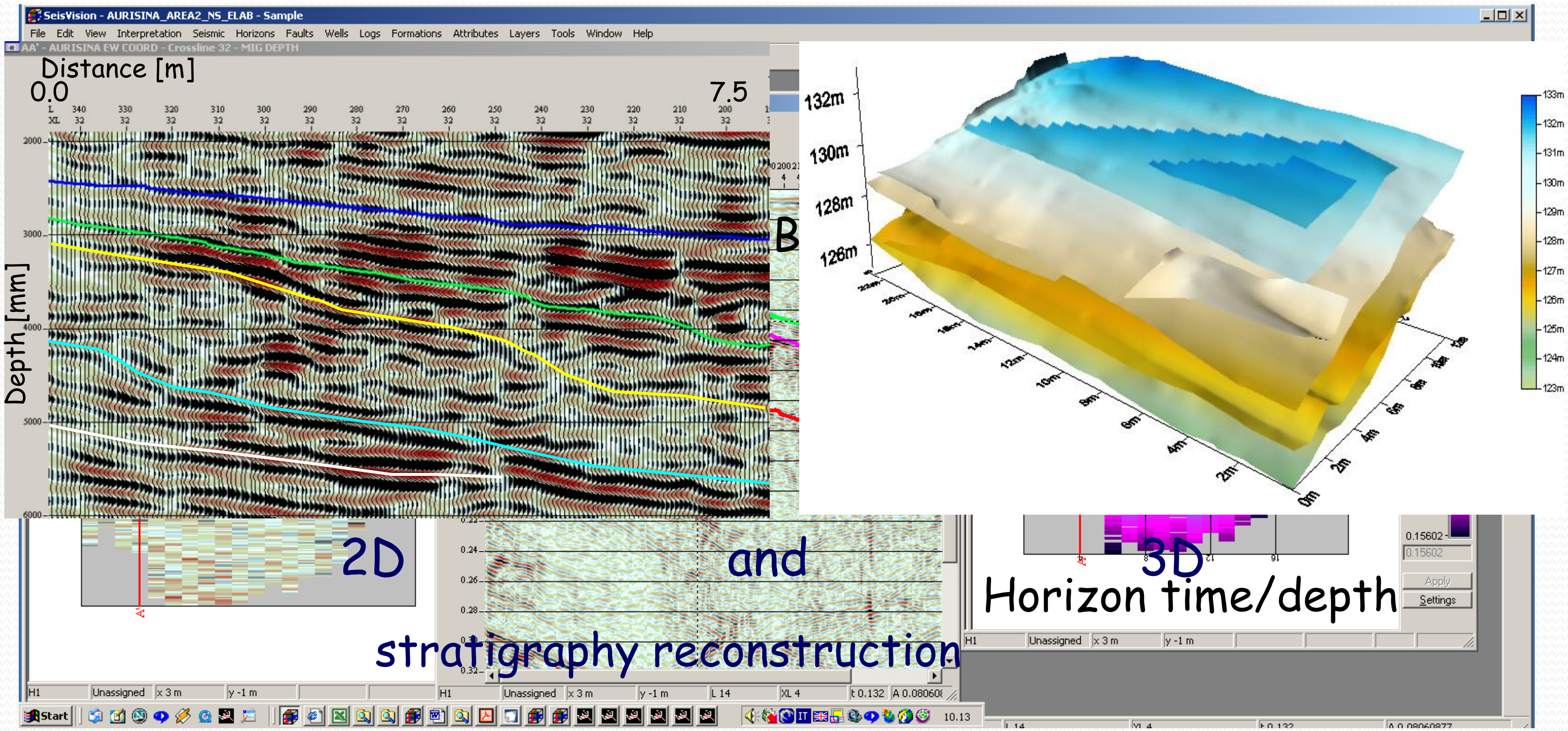
..3-D subsurface models





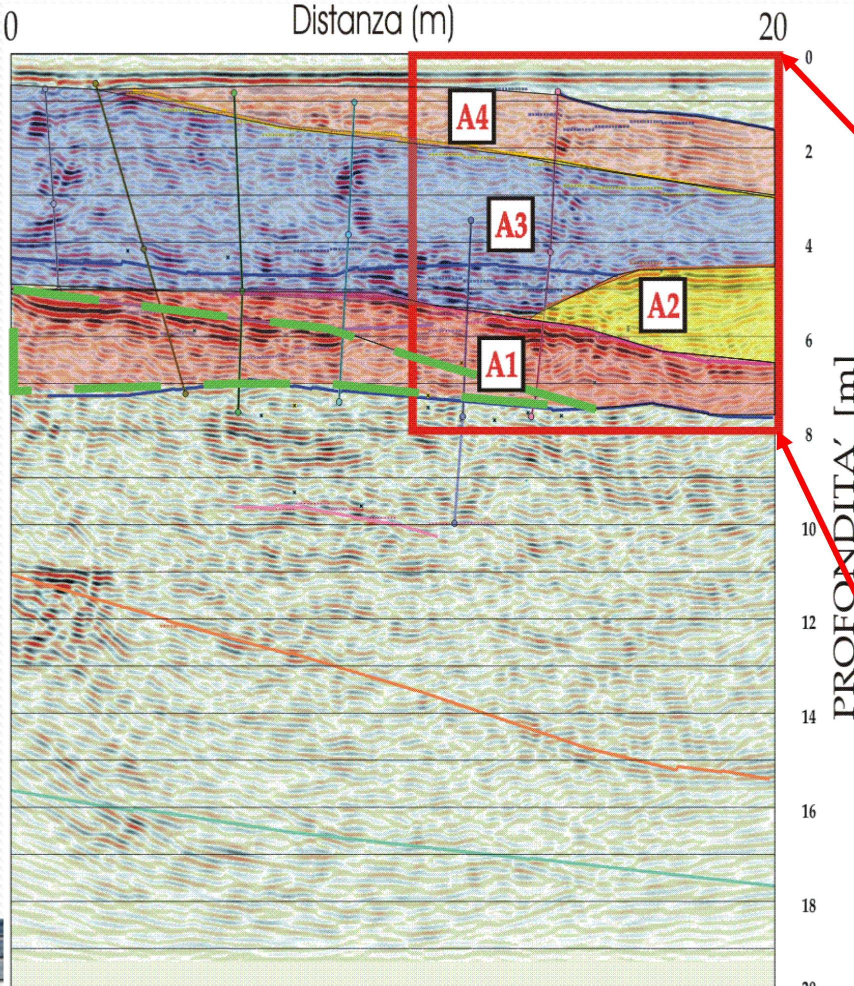
Data integration-interpretation

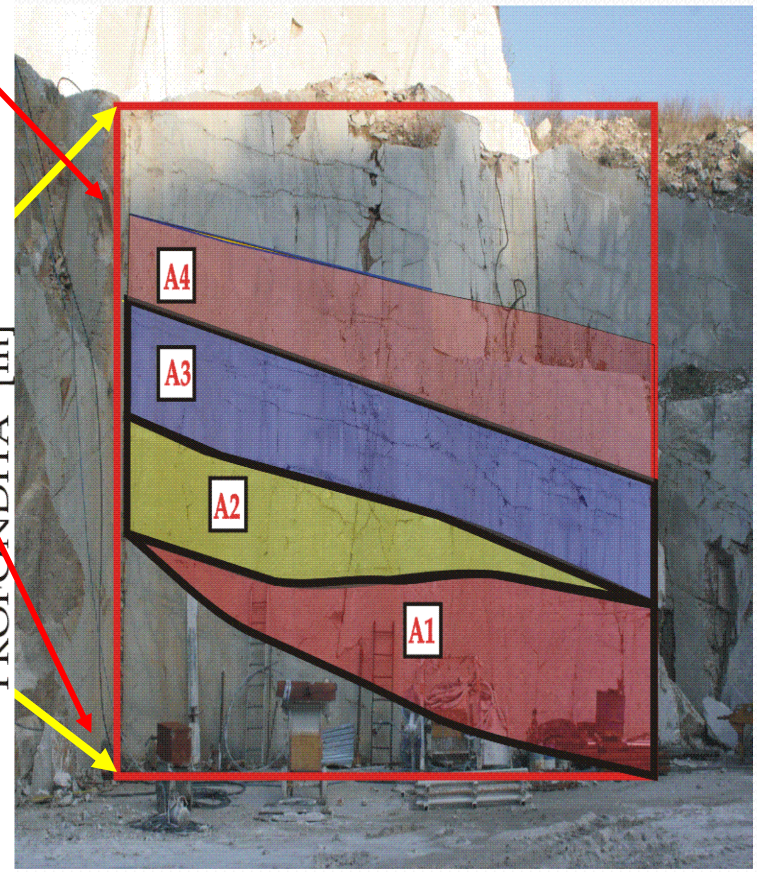
From 2D interpretation to 3D stratigraphy reconstruction



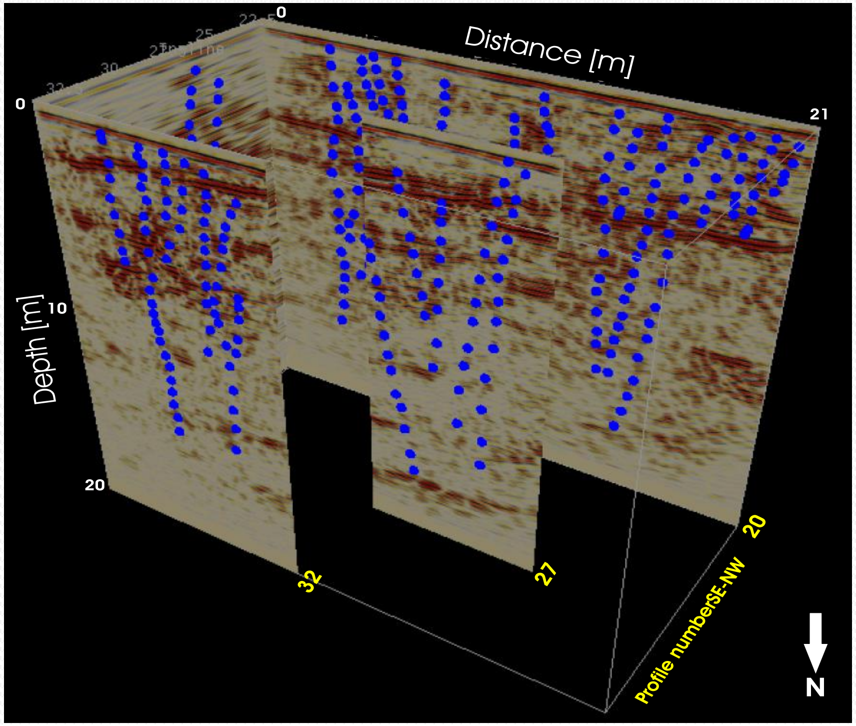
Data integration-interpretation

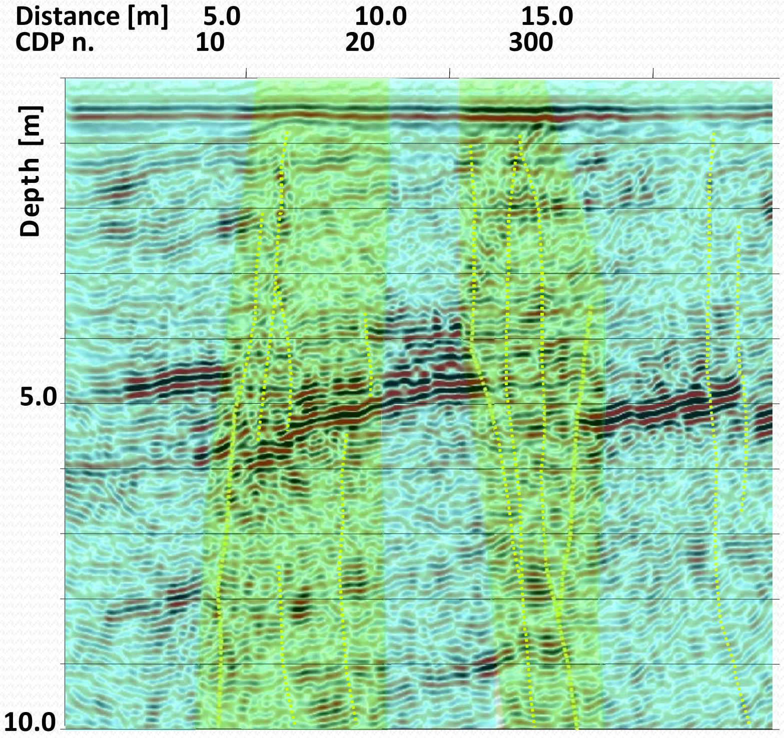
Correlation, calibration and validation with outcrops





Data integration-interpretation





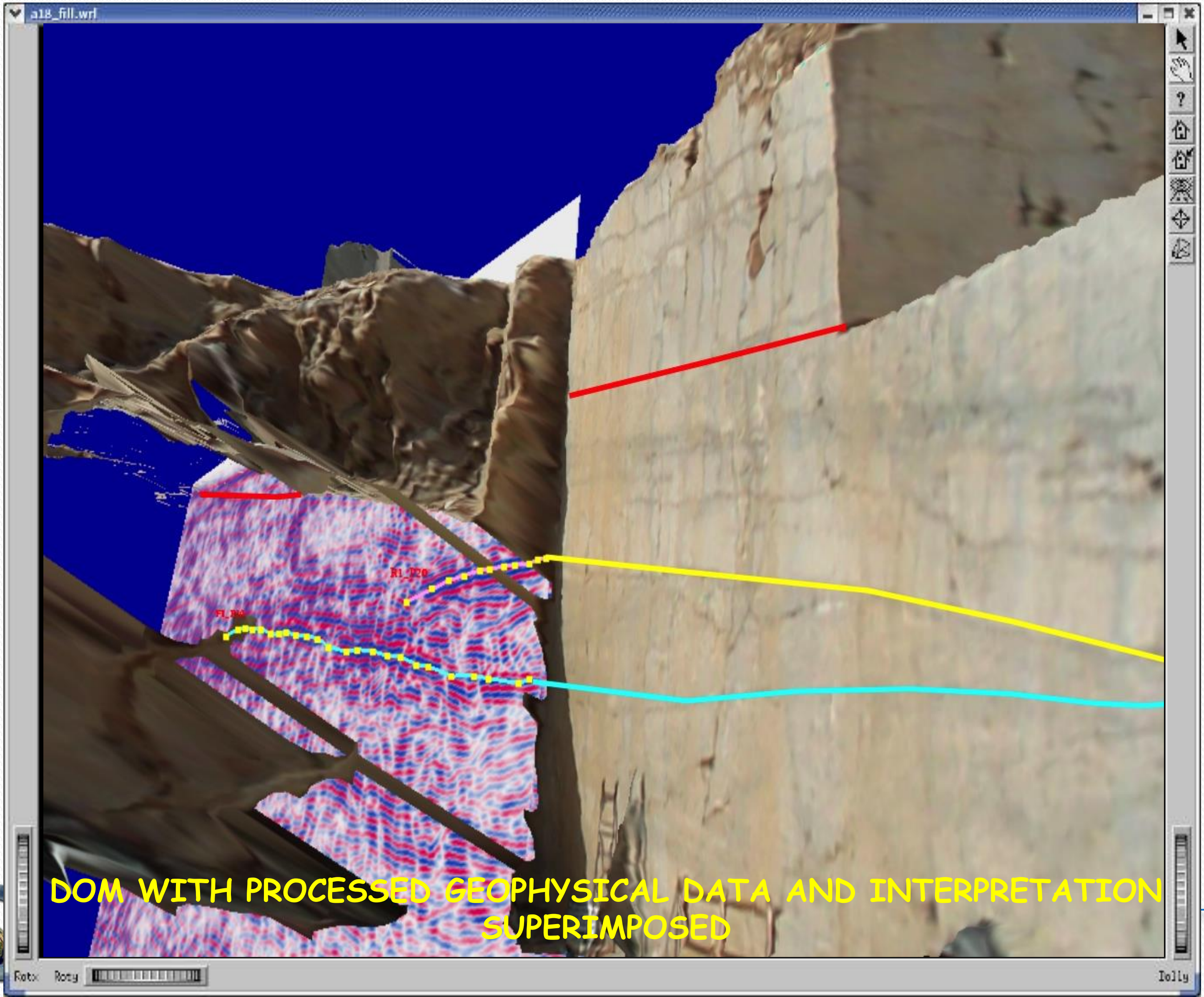
3D Discontinuities mapping and

HIGH fractures density

LOW fractures density

Homogeneous zones definition ➔ geomechanic rock characterization

3D data integration, visualization and analysis



Interpretation pitfalls structural

Associated with

- VELOCITY: because seismic data are often displayed in time rather than in depth
- GEOMETRY: because seismic events from a 3D world are displayed in a 2D section
- RECORDING/PROCESSING: because the content of a seismic section is not only geological and the non-geological components can mask geology (e.g., multiple reflections)

Interpretation pitfalls material characterization

EXAMPLE: Bright spot and false bright spot (bright spot is a DHI, i.e., a direct hydrocarbon indicator)

- Gas/light oil in soft sand increase compressibility, decrease velocity, produce strong negative amplitude anomalies (negative bright spot)

Interpretation pitfalls material characterization

EXAMPLE: Bright spot and false bright spot (bright spot is a DHI, i.e., a direct hydrocarbon indicator)

- Hard sand saturated by brine may induce a (positive) bright spot
- Gas-filled sand may be transparent, thus causing a weak reflection (dim spot)

But…

Interpretation pitfalls material characterization

EXAMPLE: Bright spot and false bright spot (bright spot is a DHI, i.e., a direct hydrocarbon indicator)

They can be associated with

- Volcanic intrusions and volcanic ash layers
- Sands with calcite cement in thin pinch-outs
- Low-porosity heterolithic sands
- Overpressured sand or shales
- Coal beds
- Top of salt diapirs

The last three have the same polarity of gas sands

Interpretation pitfalls material characterization

EXAMPLE: define a unique standard

American vs. European polarity

- American: increase in impedance gives positive amplitude (normally black in VA or red in VD)
- European and Australian: Increase in impedance gives negative amplitude (normally white in VA or bluein VD)

Interpretation pitfalls material characterization

EXAMPLE: HARD (meaning high impedance) vs. SOFT (meaning low impedance) events

HARD

- Shallow sands at normal pressure embedded in pelagic shales
- Cemented sandstones with brine saturation
- Carbonate rocks embedded in silicoclastics
- Mixed lithologies like shaly sands, marls, volcanic, ashes

SOFT

- Pelagic shale
- Shallow unconsolidated sands (any pore fluid) embedded in normally compacted shales
- Hydrocarbon accumulations in clean, unconsolidated sands
- Overpressured zones

How to extract more geology out of 3-D seismic data

- Expect detailed subsurface information
- Do not rely on “automatic” procedures to find answers
- Use all the data
- Understand the data and appreciate its defects
- Use time (or depth) slices/horizontal sections
- Visualize subsurface structure
- Use machine autotracking and snapping
- Select the color scheme with care
- Question data phase and polarity
- Tie seismic data to well data on character
- Believe seismic amplitudes
- Understand the seismic attributes you use
- Prefer horizon attributes to windowed attributes
- Use techniques that maximize signal-to-noise ratio

Conclusions

- 3-D seismic imaging is a powerful tool to:
  - unravel complex structural features
  - identify faults and fractures with adequate precision for exploratory/production drilling purposes
  - obtain detailed 3-D structural models of use in the identification and assessment of geothermal resources

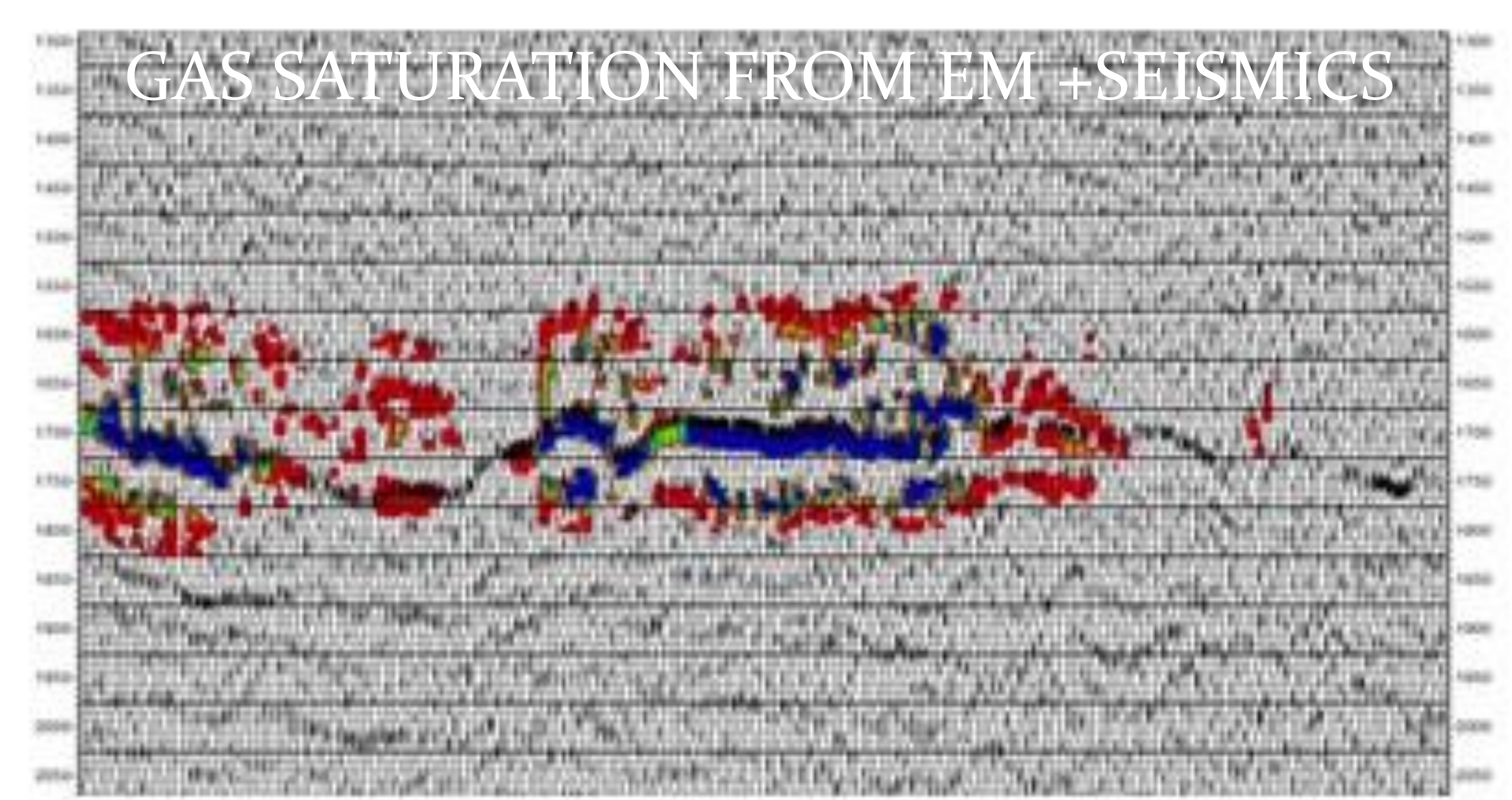
NONETHELESS…

Conclusions (2)

- Seismic data are sensitive to acoustic impedance contrasts
- Different types of fluids and/or variations of temperature may have little effect on acoustic impedance
- Even seismic AVO response and instantaneous seismic attributes do not allow convincing discrimination between fluid/lithology variations

THEREFORE…

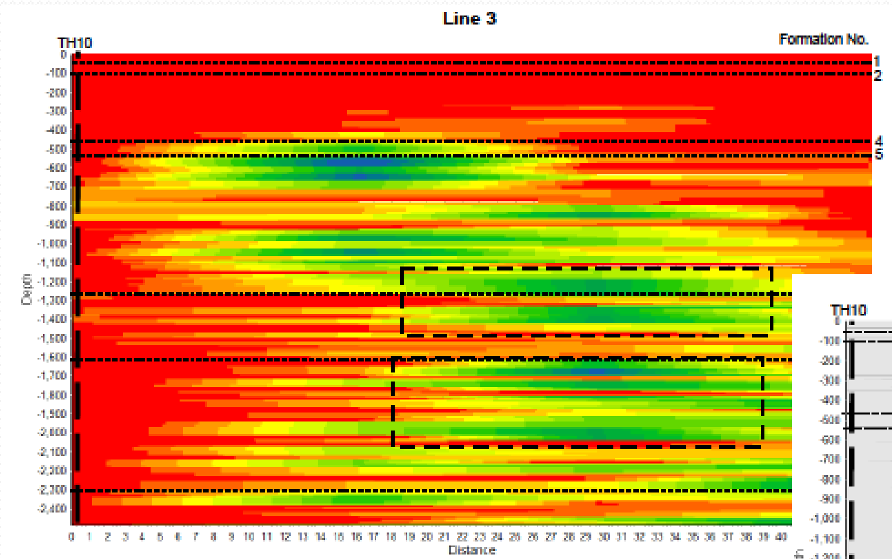
THE ROAD AHEAD IN GEOTHERMAL EXPLORATION:
Joint Seismic/EM imaging and inversion



THE ROAD AHEAD IN GEOTHERMAL EXPLORATION: joint application for detecting hydraulic properties

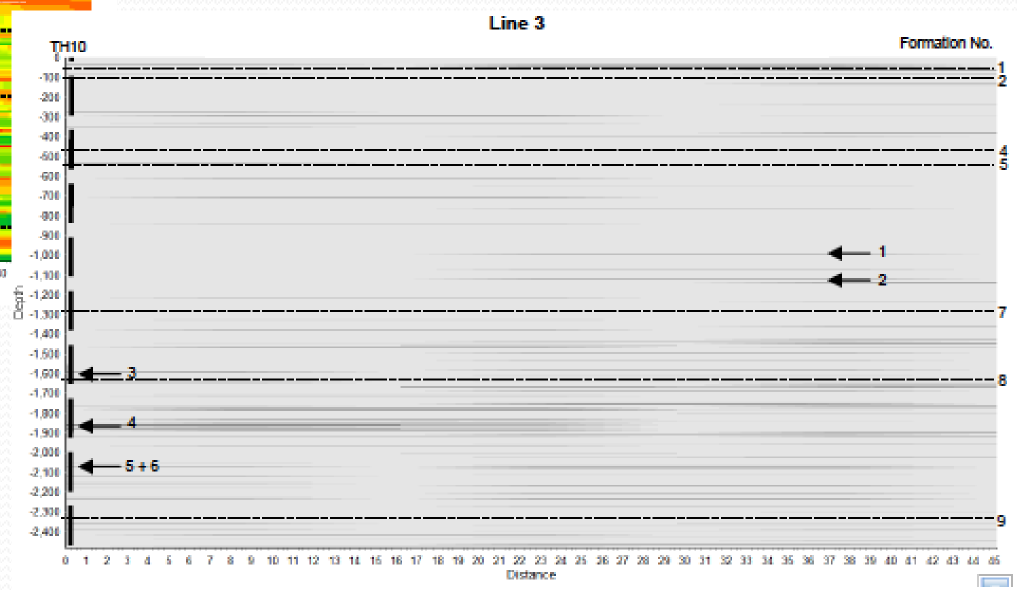
New estimates are under study, to improve technology.
For example, the **electro seismic effect** can be observed when a fast traveling p wave intersects a water saturated interface of differing anelastic or electrical properties. The electro seismic effect is in effect a form of converted energy which is released as dissipated energy. This conversion of energy takes place when a fast moving P waves produce slower P waves as it passes through the interface. These slow P waves produce much more movement between the rock and water. This in turn leads to a high loss of energy in the form of heat due to friction and electro seismic effects, such as electromagnetic radiation due to ionic movement. Electro seismic signals are produced by the out of phase motion between all the ions in the water and those attached to the rock.

THE ROAD AHEAD IN GEOTHERMAL EXPLORATION: joint application for detecting hydraulic properties



From M.Du Preez, J.R. Mc Kendry

Deep Aquifer Electro Seismic Coupling Coefficient analysis (Depth and distance in meters)



Fracture analysis (Depth and distance in meters)

Some example of application

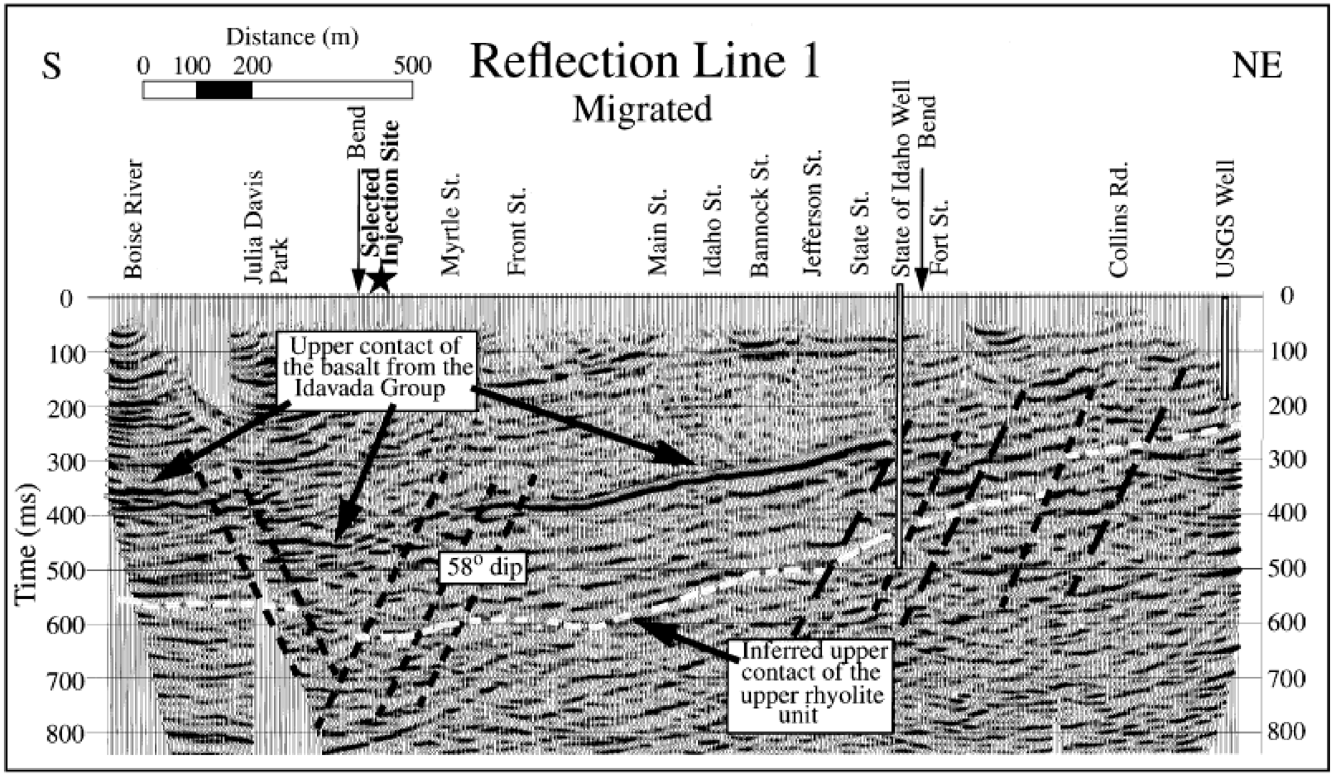
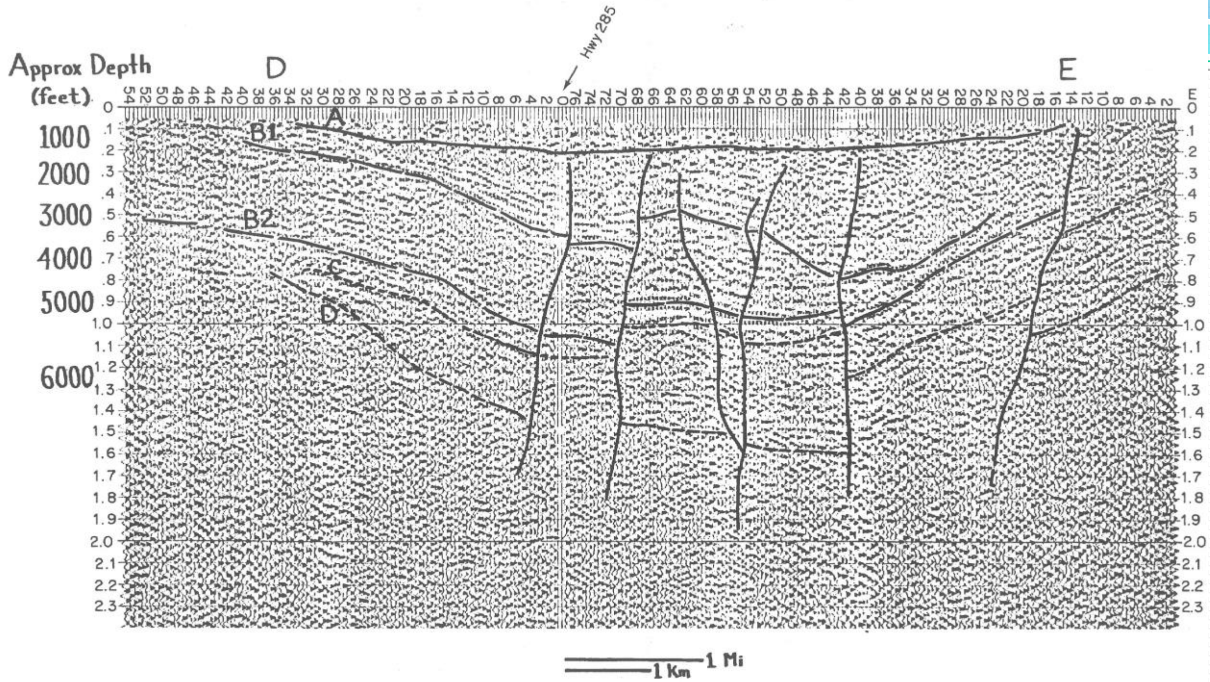


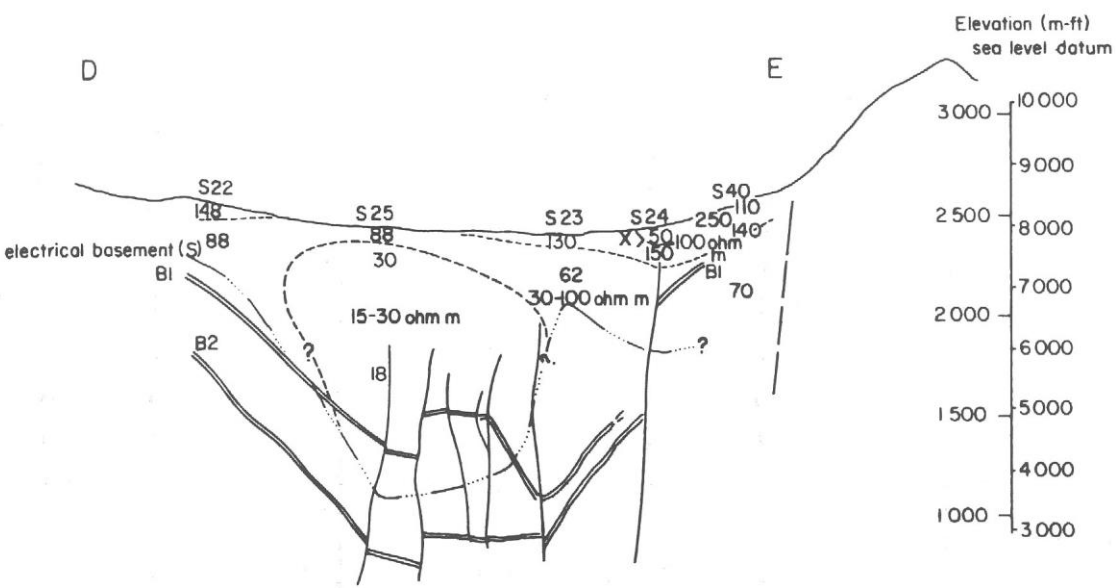
FIG. 9. Migrated north-south seismic line with interpretation. The selected site for the new injection well is located in a region with suspected faults in the geologic units associated with the geothermal aquifer. The estimated depth to the upper contact of the upper rhyolite member is projected from the depth recorded in the State of Idaho injection well and the assumption of a constant thickness volcanic assemblage. The section has no vertical exaggeration for 2000 m/s twtt.

Liberty, 1998)

Well siting for reinjecting spent geothermal fluid based on geothermal aquifer depth, location of interpreted faults, projected thermal impact of injection on existing wells, surface pipe extension costs, and public land availability.

Seismic data estimated the depth and continuity of a basalt and rhyolite volcanic sequence and fault location.

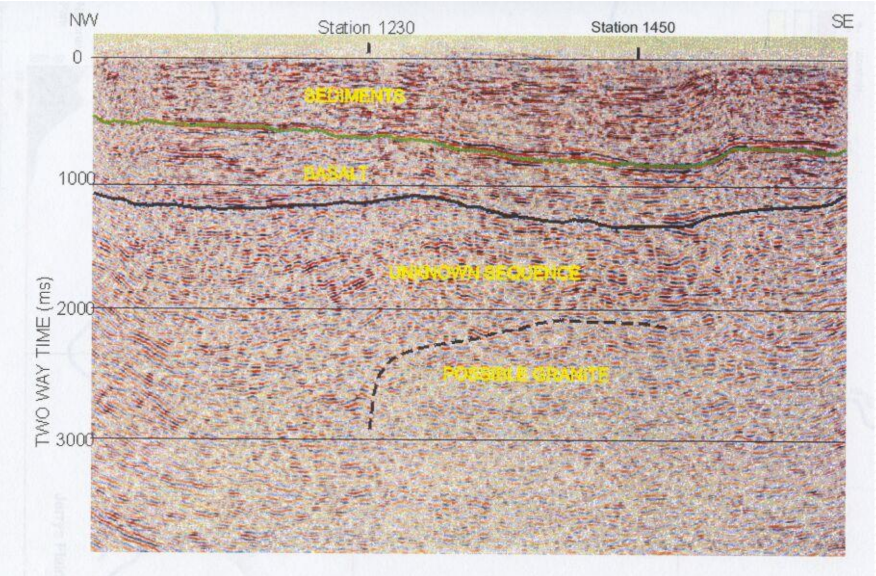




Good-quality seismic sections can be obtained also in volcanic terrain, as in this example obtained in an area where basalt flows are interbedded with gravels and shale or alluvium.

An area of relatively low resistivity, which is believed to represent the reservoir feeding the mineral hot springs, is seen to be associated with a down-drop fault block that is traced by the surface of the basalt flows.

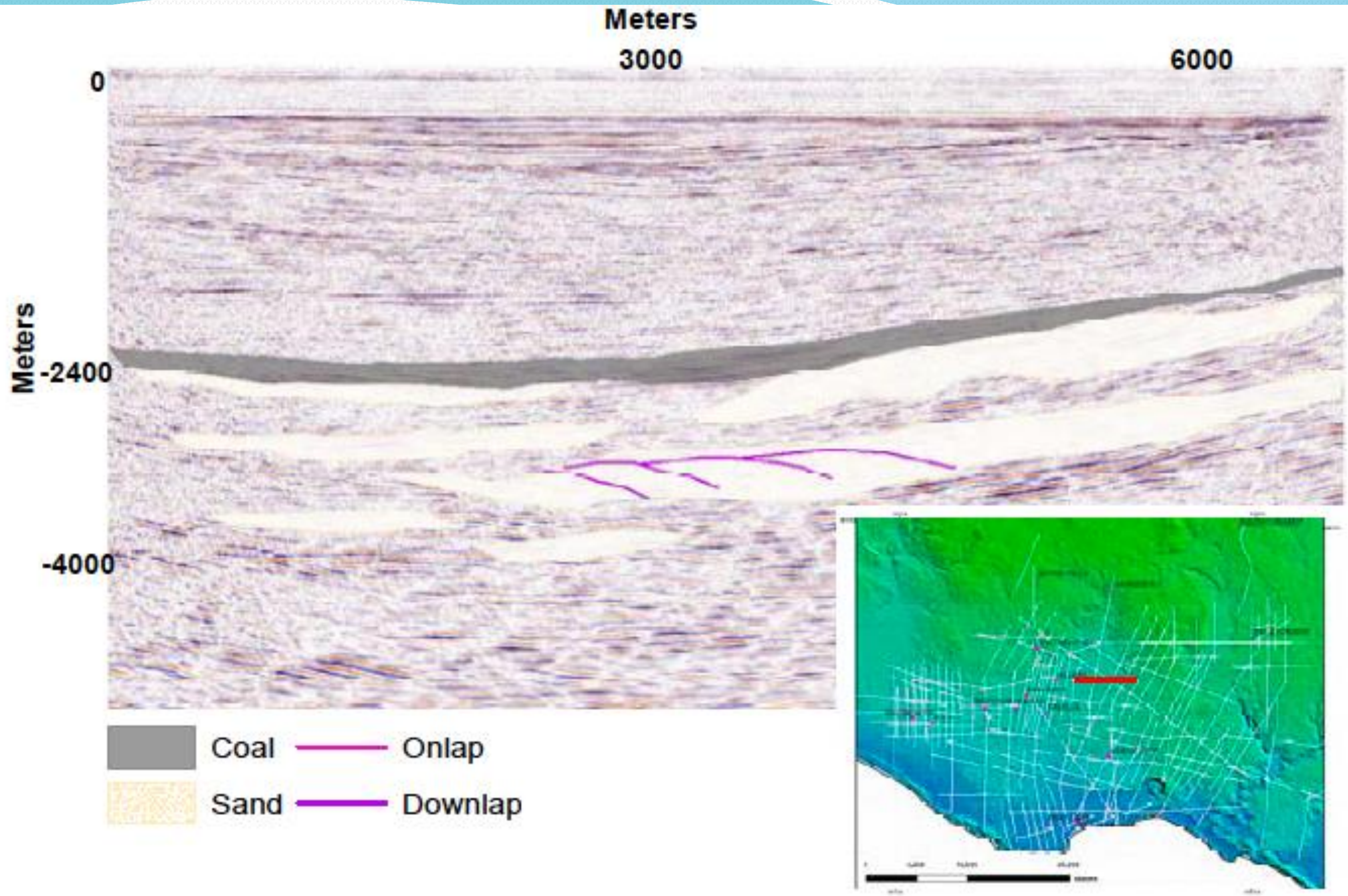
From Keller, 1972



SEISMIC LINE JP-01
INTERPRETED SECTION TO 4,000 ms – PLAN NO 13

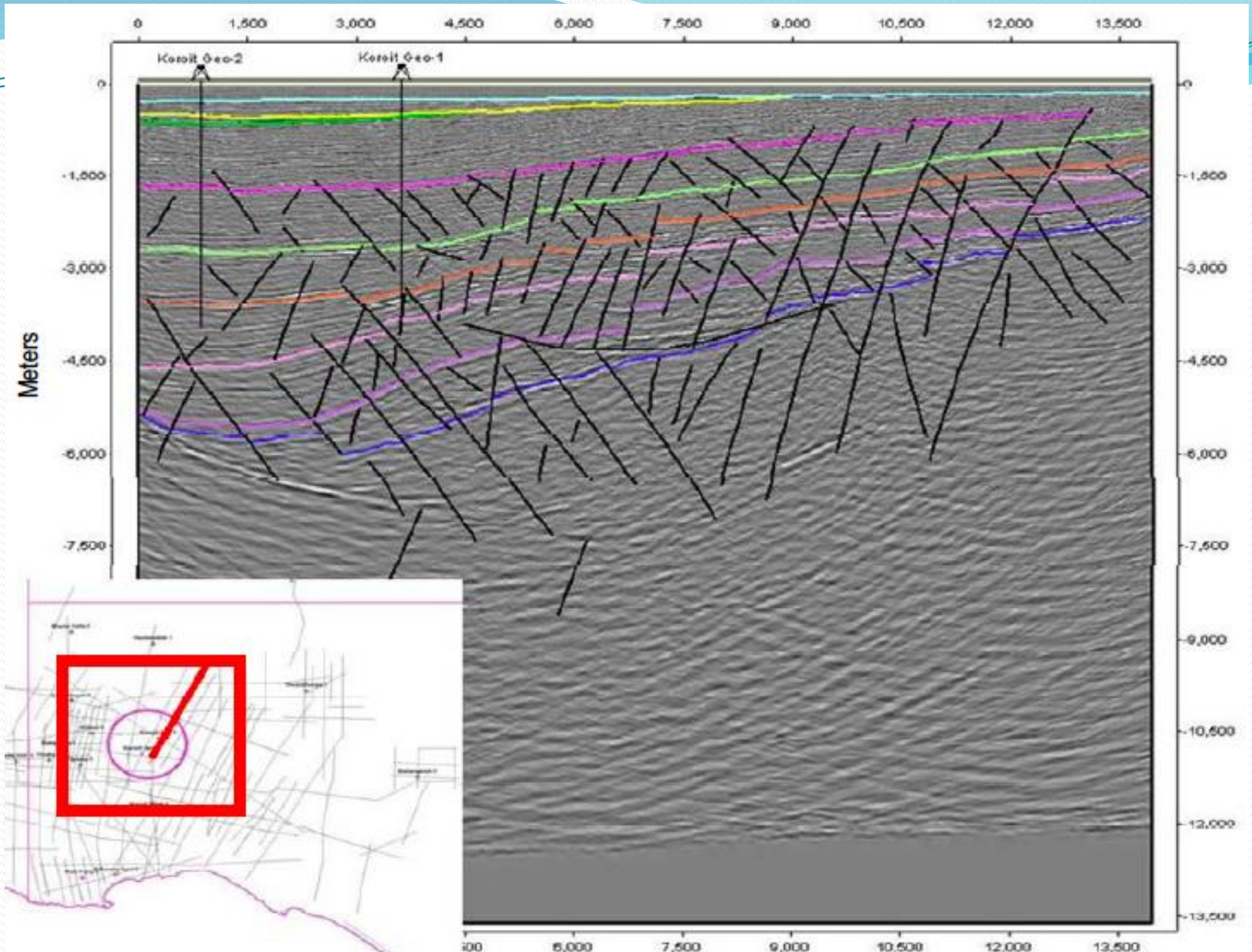
A 19km long seismic reflection survey was then carried out along an east-west track over a heat flow anomaly. Analysis of the seismic results and those from a micro-gravity study along the same track suggested that a buried granite probably exists at a depth of at least 5km. The geothermal anomaly is apparently due to radiogenic heat production in this buried granite, which means that the granite represents a substantial source of energy.

The results of the project stimulated commercial interest in Australia's hot dry rock resources



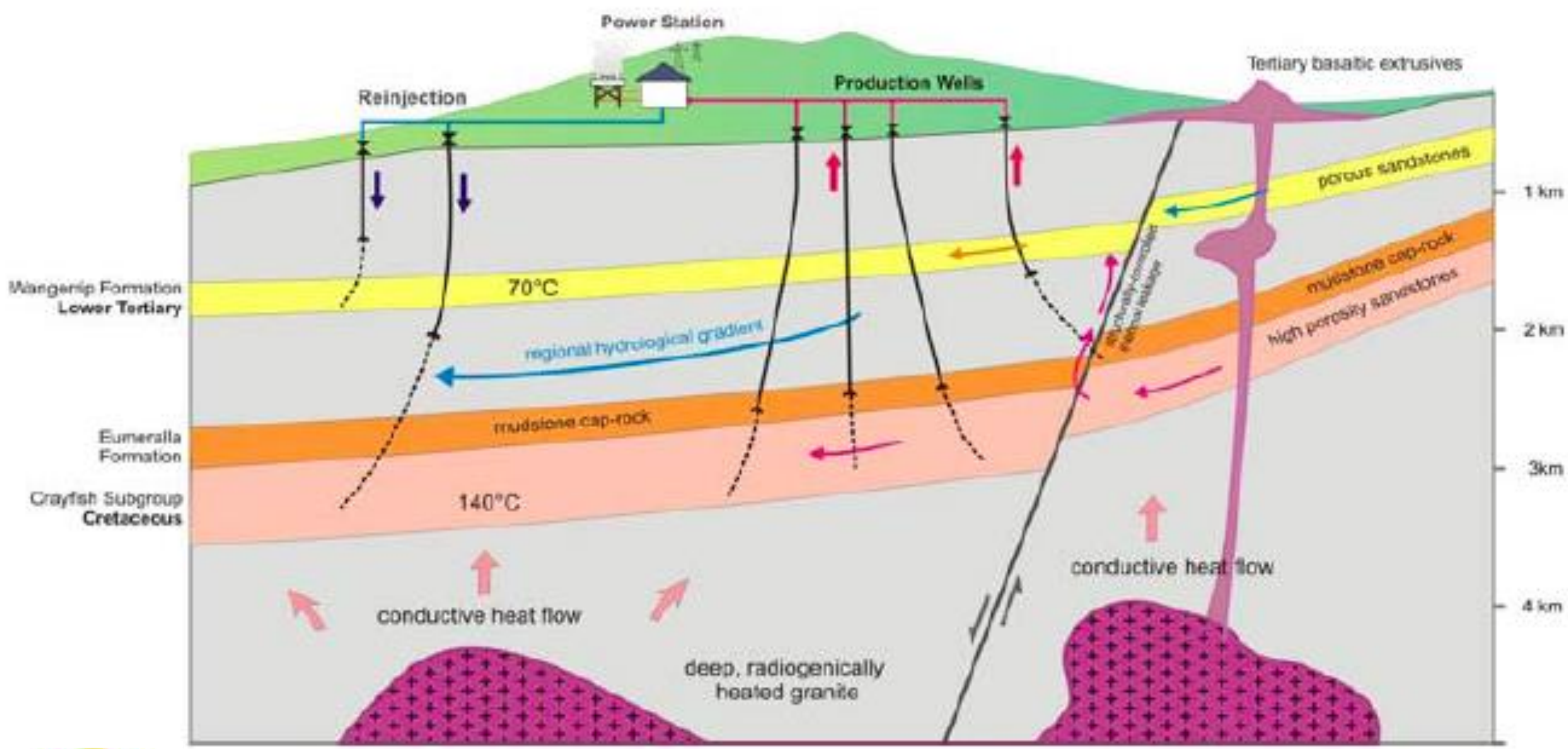
Sands represent a prime geothermal target with potentially high porosities and at sufficient depth to reach attractive geothermal temperatures in the range of 140 to 180oC.

Assessment Report, 2009



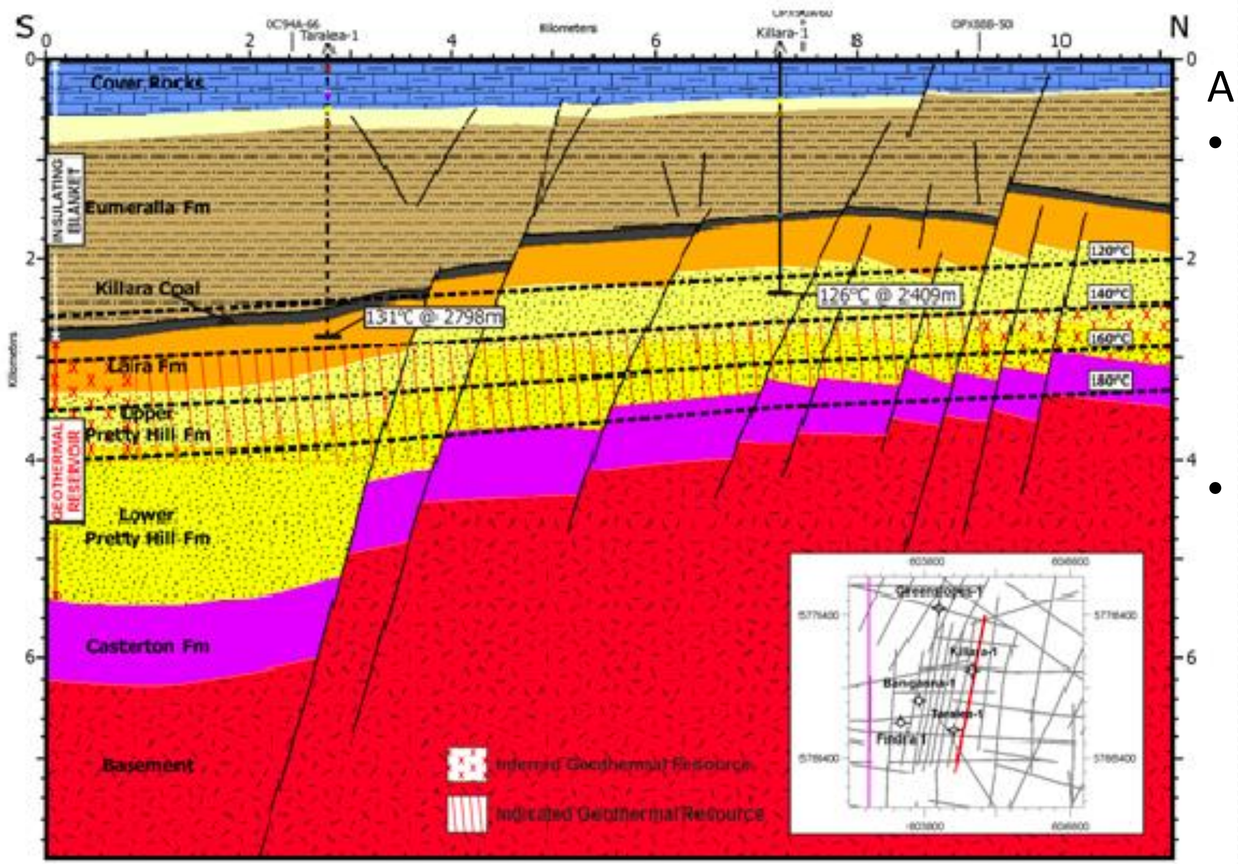
Detailed interpretation of faults and fractures along depth seismic survey line

Assessment Report, 2009



Schematic hydrogeological/geothermal production model

Assessment Report, 2009



Australian G. Code:

- Inferred Geothermal Resource is where indirect methods are used to assess geothermal thermal energy in place.
- Indicated Geothermal Resource is that part of a geotherma resource that has been demonstrated to exist through actual measurement of temperature and resource dimensions.

hotrock

Assessment Report, 2009

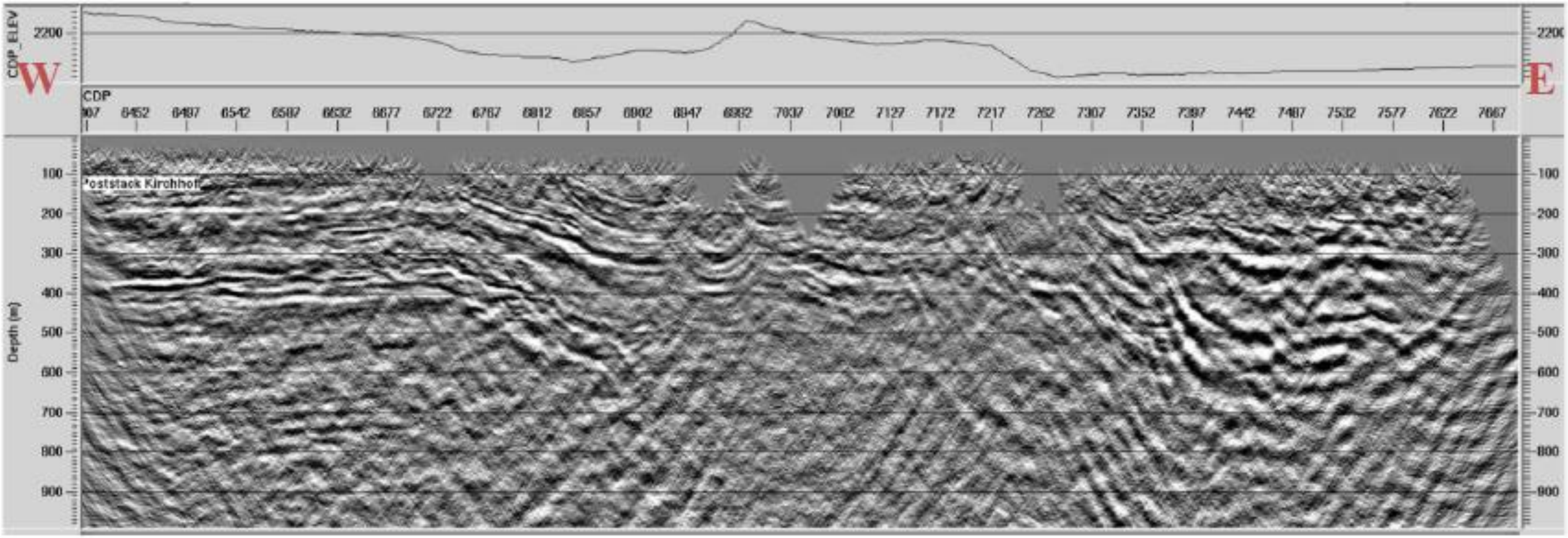


Figure 5.8: It shows the depth converted section of Kirchhoff time migration stack without interpretation.

Report on geophysical investigation, 2013

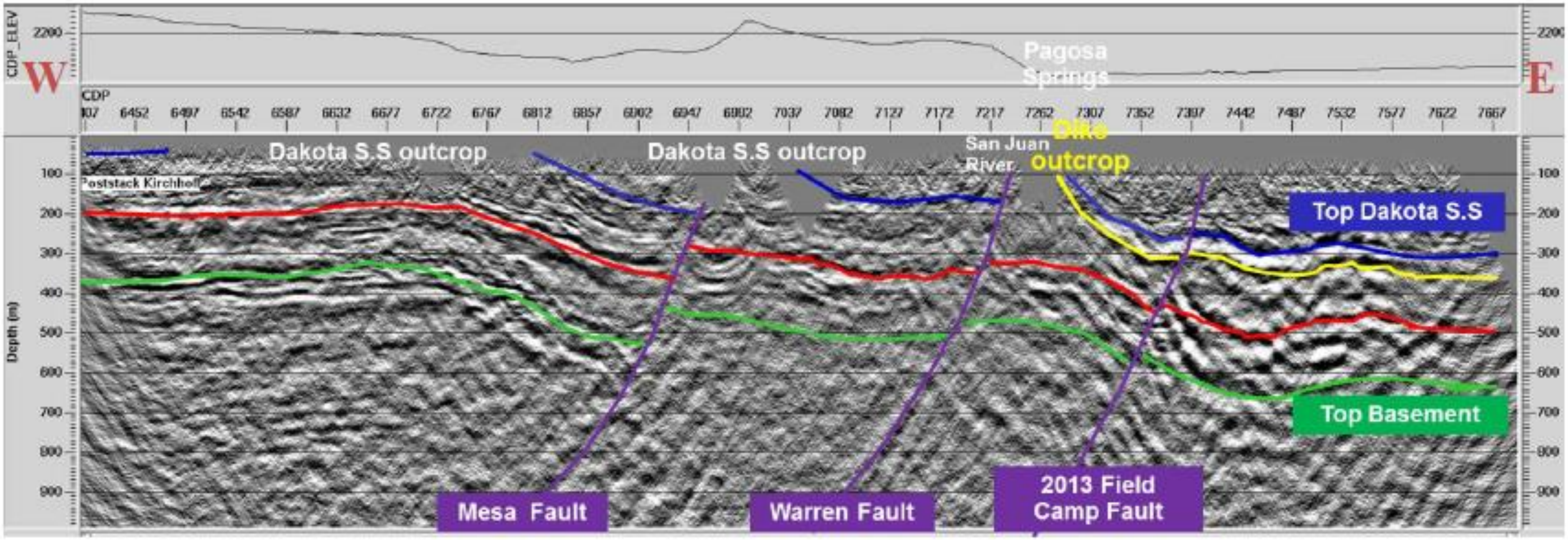


Figure 5.9: It shows the depth converted section of Kirchhoff time migration stack with interpretation.

Report on geophysical investigation, 2013

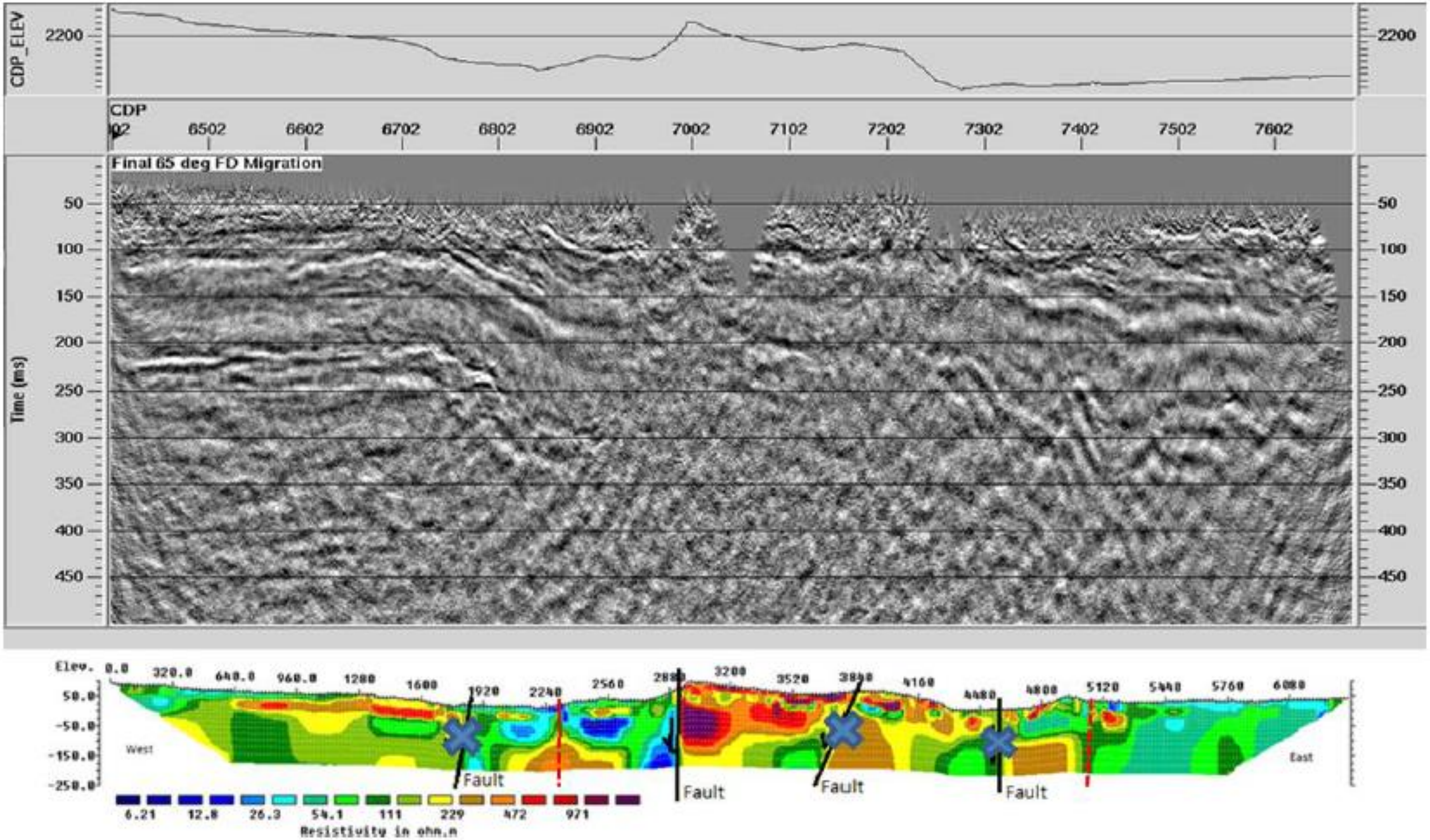


Figure 10.20: Deep Seismic and DC Resistivity Overlay

Report on geophysical investigation, 2013

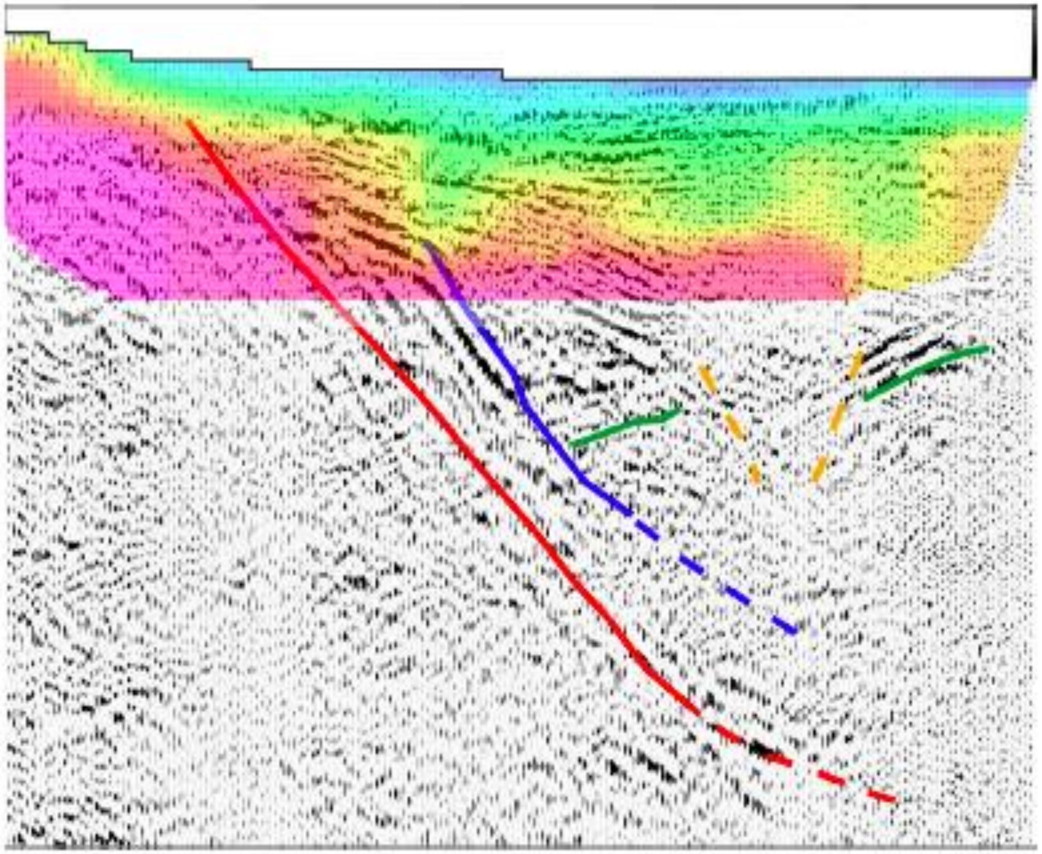


Figure 1: Advanced seismic imaging section from a geothermal prospect in northern Nevada. The optimized velocity section is superimposed on the black-and-white reflection section. Faults are marked as colored lines, with the rangefront fault in red.

Figure shows fault-plane reflections from the rangefront fault, red, but the blue basinward fault is marked by particularly strong direct reflections from the fault plane.
These appear as strongly as any of the other reflections, perhaps indicating the higher concentration of fluids found in a geothermal reservoir.

From Louie, Pullammanappallil and Honjas

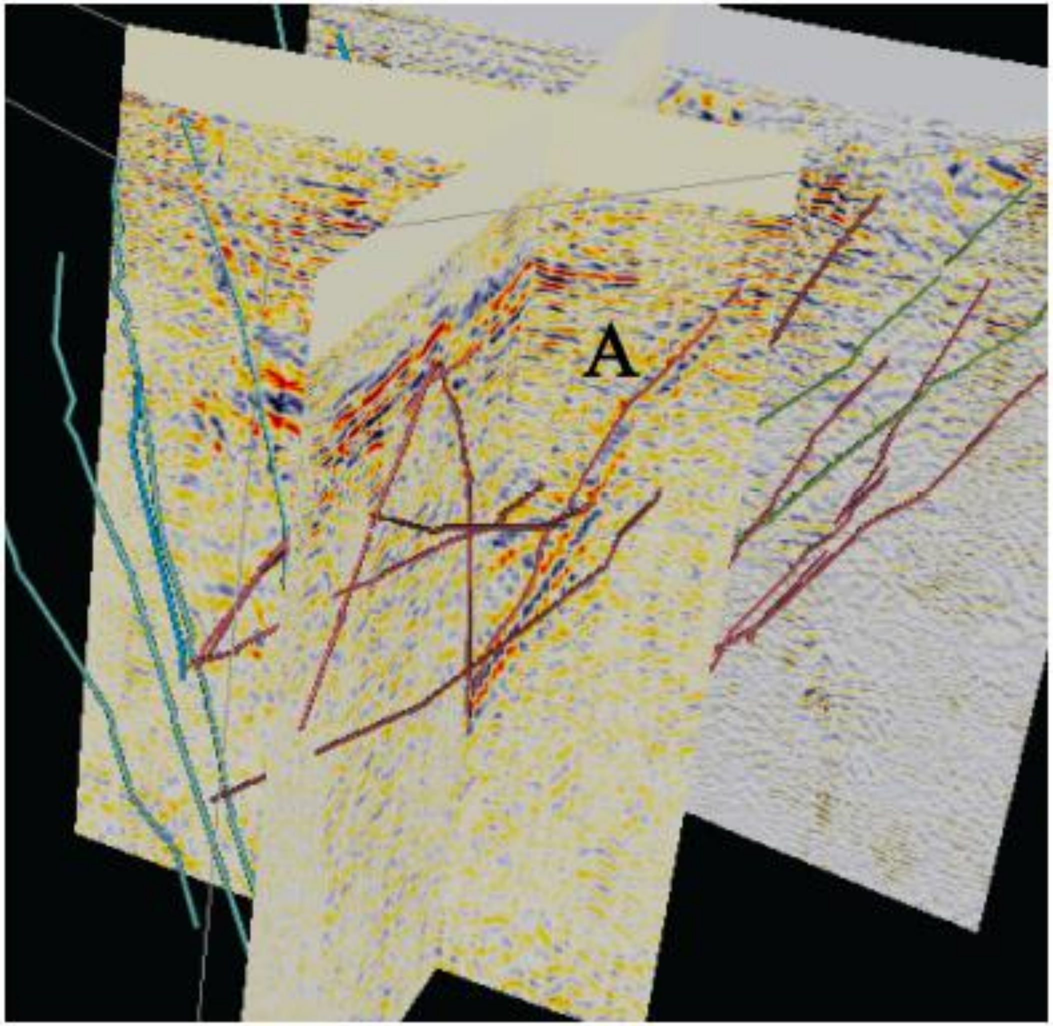


Figure 2: Advanced seismic imaging sections of a geothermal prospect near Pyramid Lake, Nevada, with a direct image of a fault plane marked with "A". From Frary et al. (2011).

Interpretations of faults across seismic lines by direct fault images and stratigraphic terminations. At a depth of 1300 m in a well drilled 6 months after completion of the seismic Surveys confirmed the fault interpreted from the advanced seismic images of several sections.

From Louie, Pullammanappallil and Honjas

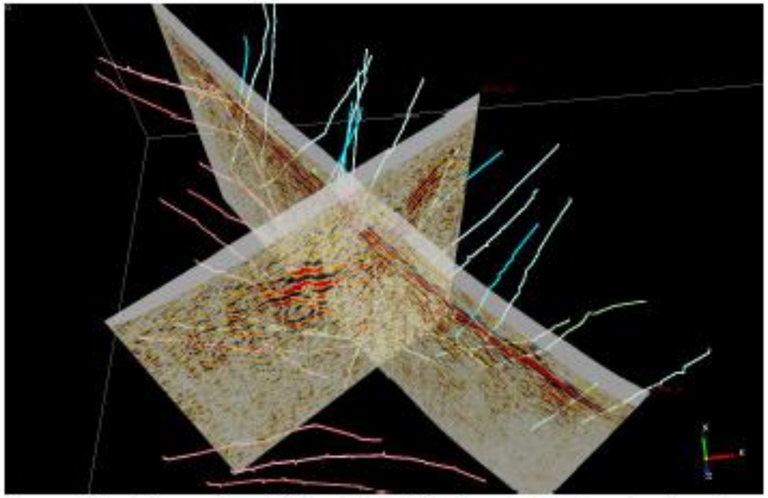


Figure 3: Alternative 3D view of advanced seismic imaging sections of a Pyramid Lake geothermal prospect, with interpreted fault sticks. From Frary et al. (2011) and Eisses et al. (2011).

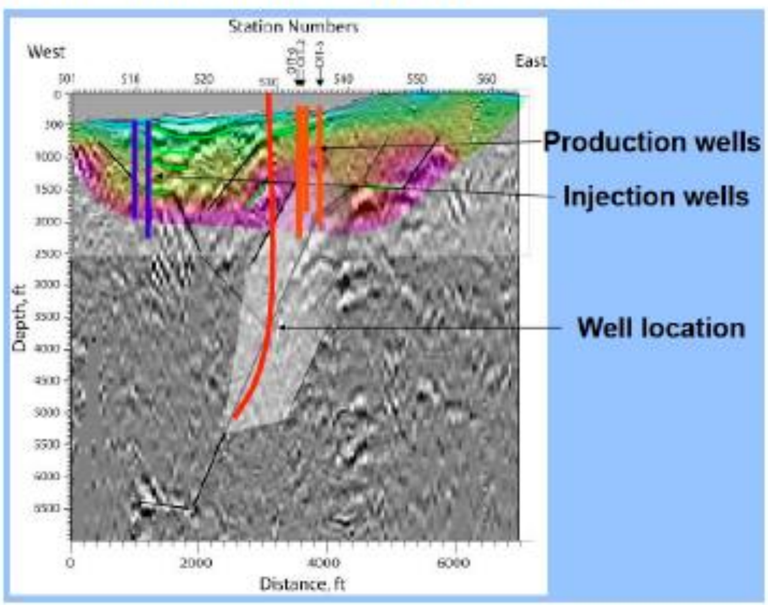


Figure 4: Advanced seismic imaging of faults (black lines) below the OIT campus in Klamath Falls, Ore. The well drilled as a result is shown in red.

This study started with an advanced seismic survey conducted in 2008 on the campus of the Oregon Institute of Technology (OIT) in Klamath Falls. Black lines on the image mark interpreted faults.

OIT located a new well (red in Figure) based on the seismic interpretation. Drilling intersected the fault within 15 m of the subsurface location predicted by the seismic program. Together with the shallower production and injection wells, the new well provides enough heat to meet 60% of the electrical needs of the entire OIT campus.

From Louie, Pullammanappallil and Honjas

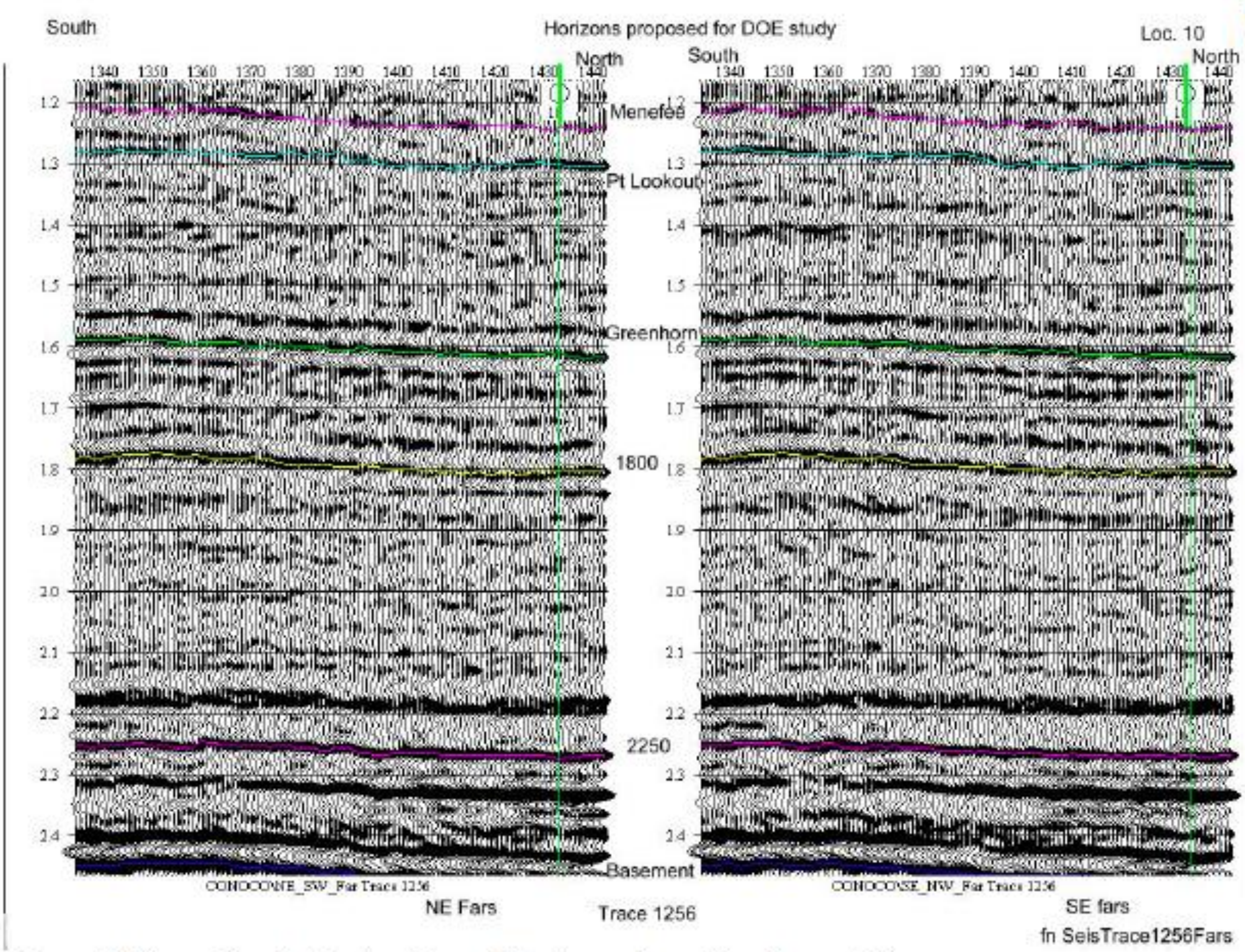
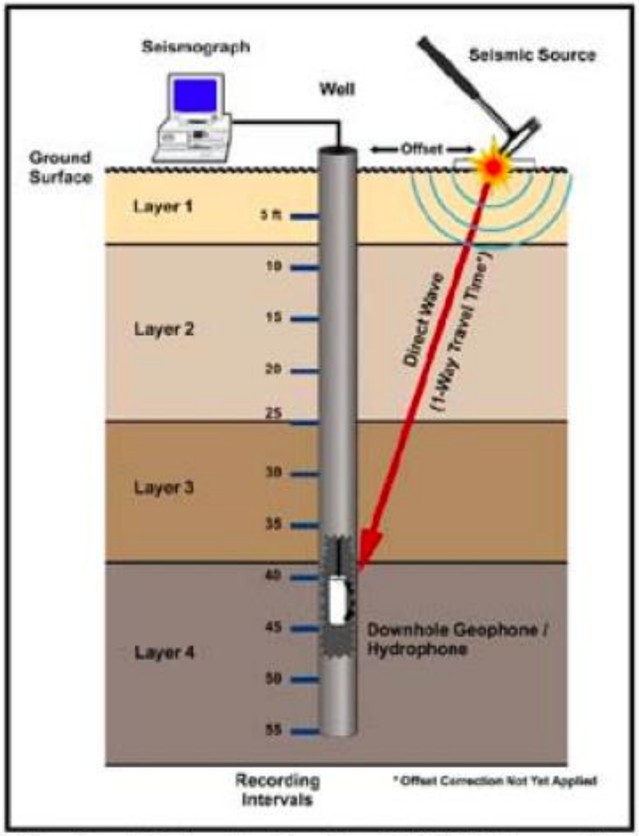


Figure 5 Example of seismic data and horizons from San Juan study.

Vertical seismic profiling (VSP)

- Geophones located downhole
- Signals made by surface explotion
- Gives the actual velocity profile
- Shows reflecting interfaces
- Waves do not pass through the earth twice, and attenuation and absorption are a minor problem



Vertical Seismic Profile (VSP) Schematic

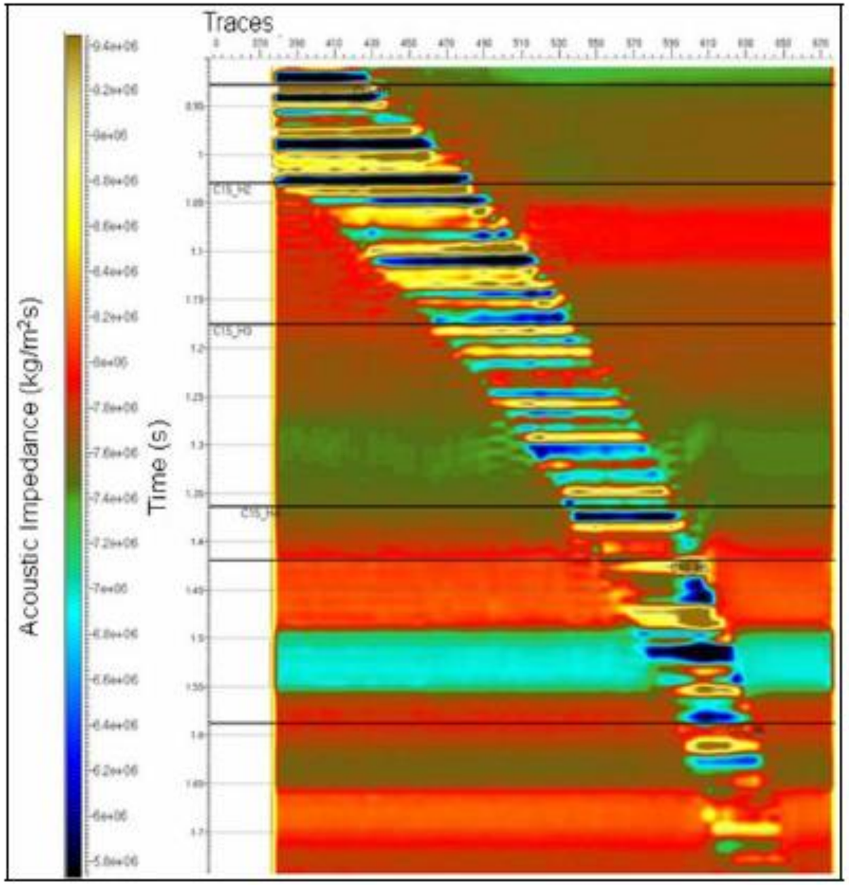


Fig. 5 Absolute impedance model calculated by seismic inversion. Dark blue colour is used for soft sediments (lower absolute acoustic impedance) and yellow represents the hard sediments (increasing acoustic impedances).

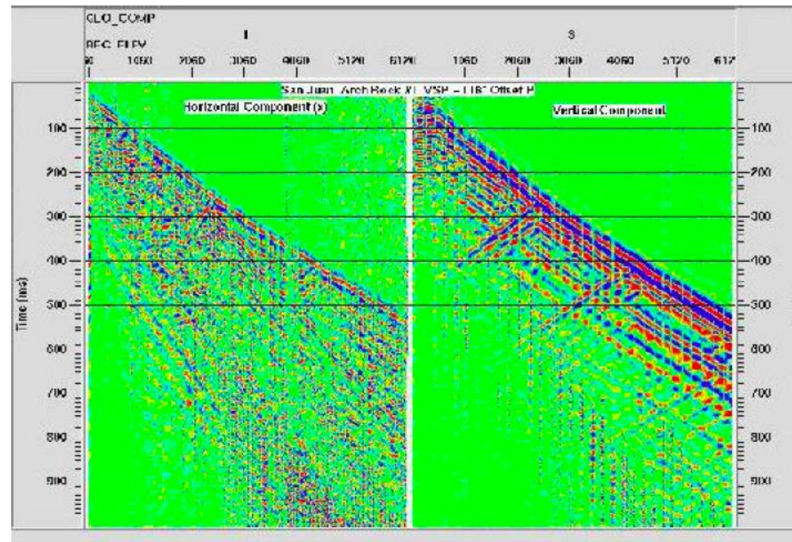


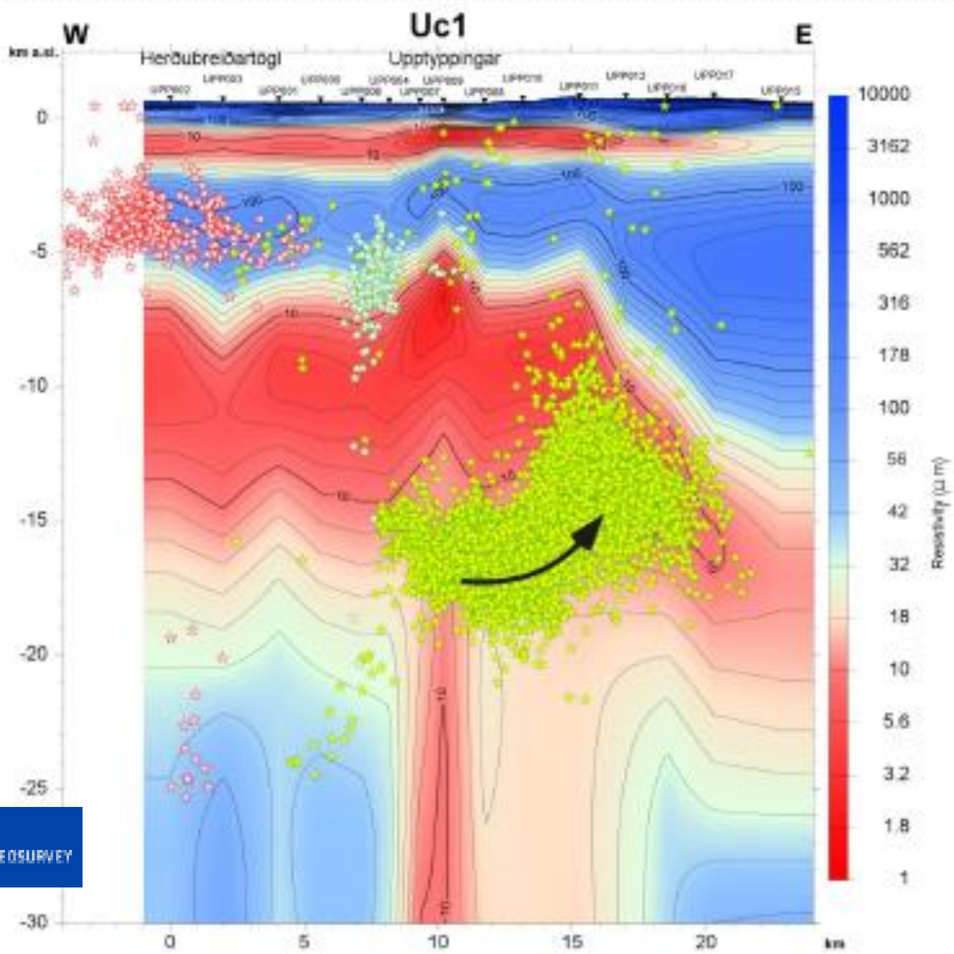
Figure 12 Portion of 9-C VSP data, P-wave.

Seismic while drilling SWD techniques

This term encompass the seismic techniques operate dwhile the drillstring is lowered in the borehone, during effective drilling or while connecting drillpipes. Various SWD techniques have been used in the industry especially for oil exploration, but various experiments have been performed also for geothermal exploration.
The most commonly used technique is the Drill-bit-SWD, that uses the acustic energy radiated by a working drill-bit.

Experiments have been performed in Italy and Nevada, most probably it will used more in the future.

Combination of passive seismic and electrical resistivity methods



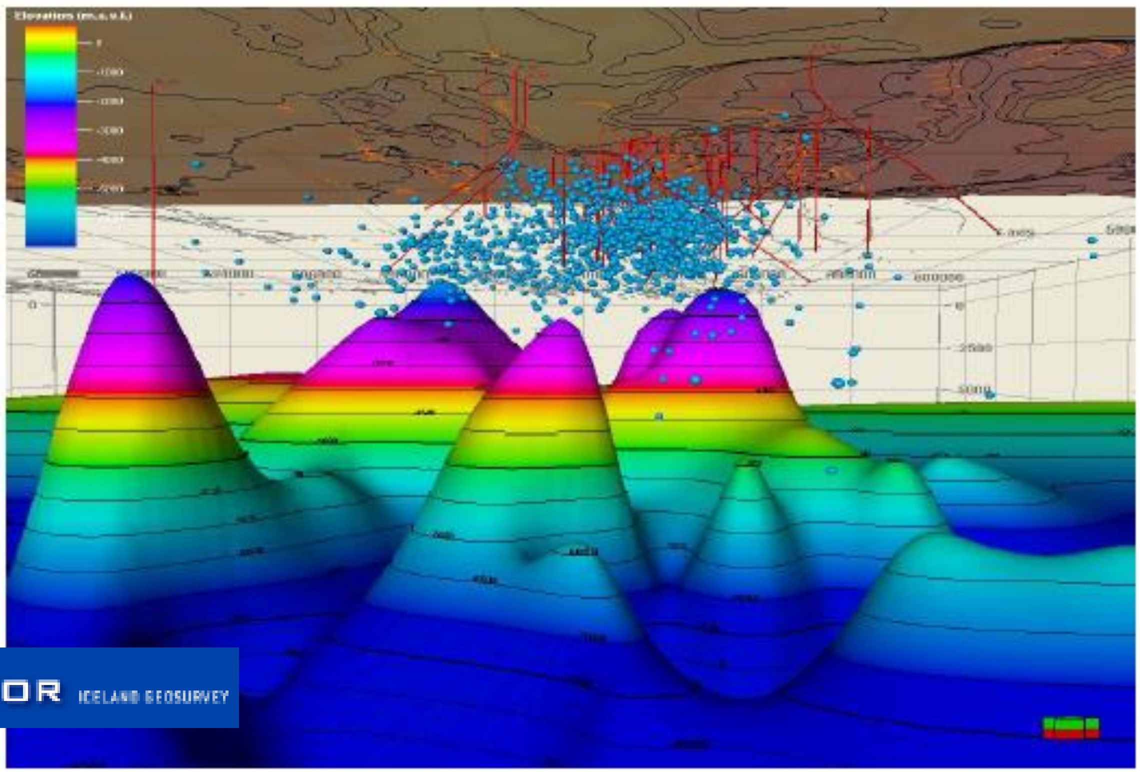
Main conductor is supposed to be the partially molten magmatic intrusions and seismic is used for identifying fractures and faults, or dykes

ÍSOR ICELAND GEOSURVEY

CNR-IGG A. Manzella

Combination of passive seismic and electrical resistivity methods

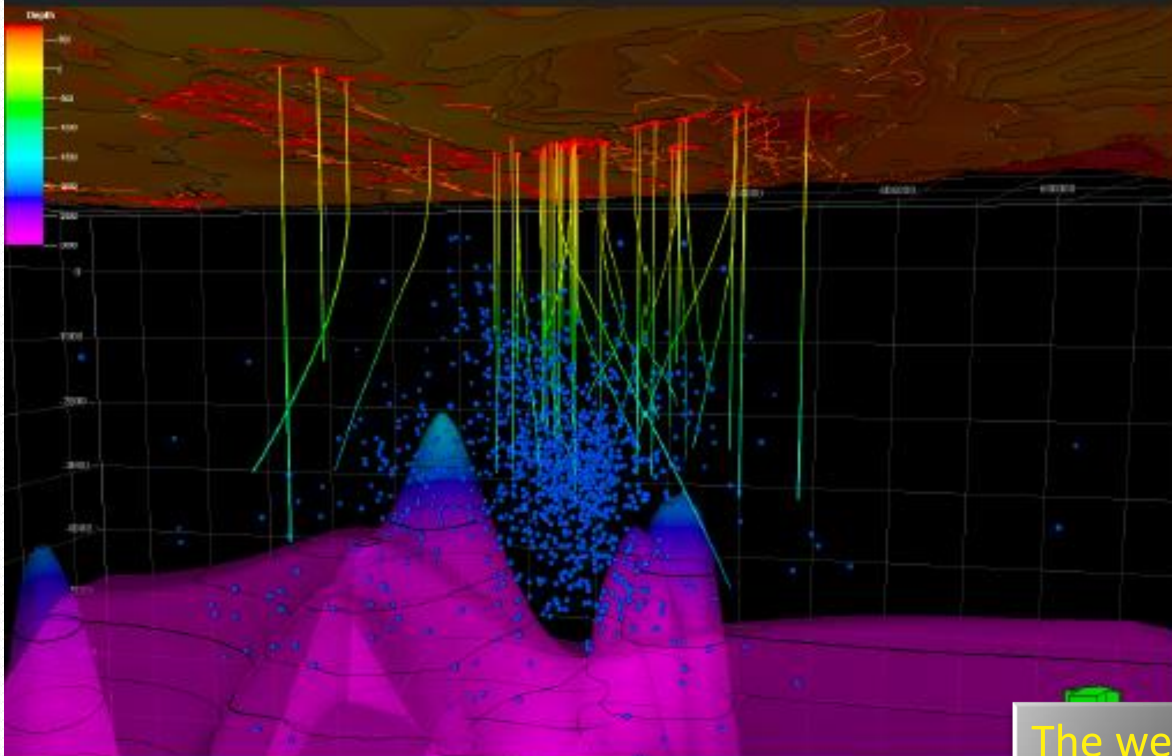
Seismicity and top of deep conductors in Krafla



Main conductor is supposed to be the partially molten magmatic intrusions and seismic is used for identifying fractures and faults, or dykes

A final word about passive techniques:

IMAGING AND CHARACTERIZATION OF DEEP GEOTHERMAL RESERVOIRS



Pre-drilling exploration results:

Resistivity shows a conductive body at average 4-5 km depth but with pinnacles up to 2km.

•Micro-earthquakes show that seismicity occurs above the conductive body indicating T higher than 700°C

Drilling results:

•A borehole pointing towards a pinnacle hit acidic magma at 2,1 km

Combined results of resistivity soundings (TEM/M
at the Krafla geothermal field (Iceland)

The well was drilled close to one of the spikes and was not intended to enter it but it did at 2.1 km depth. The data and interpretation behind the picture had uncertainty that is not described in the figure

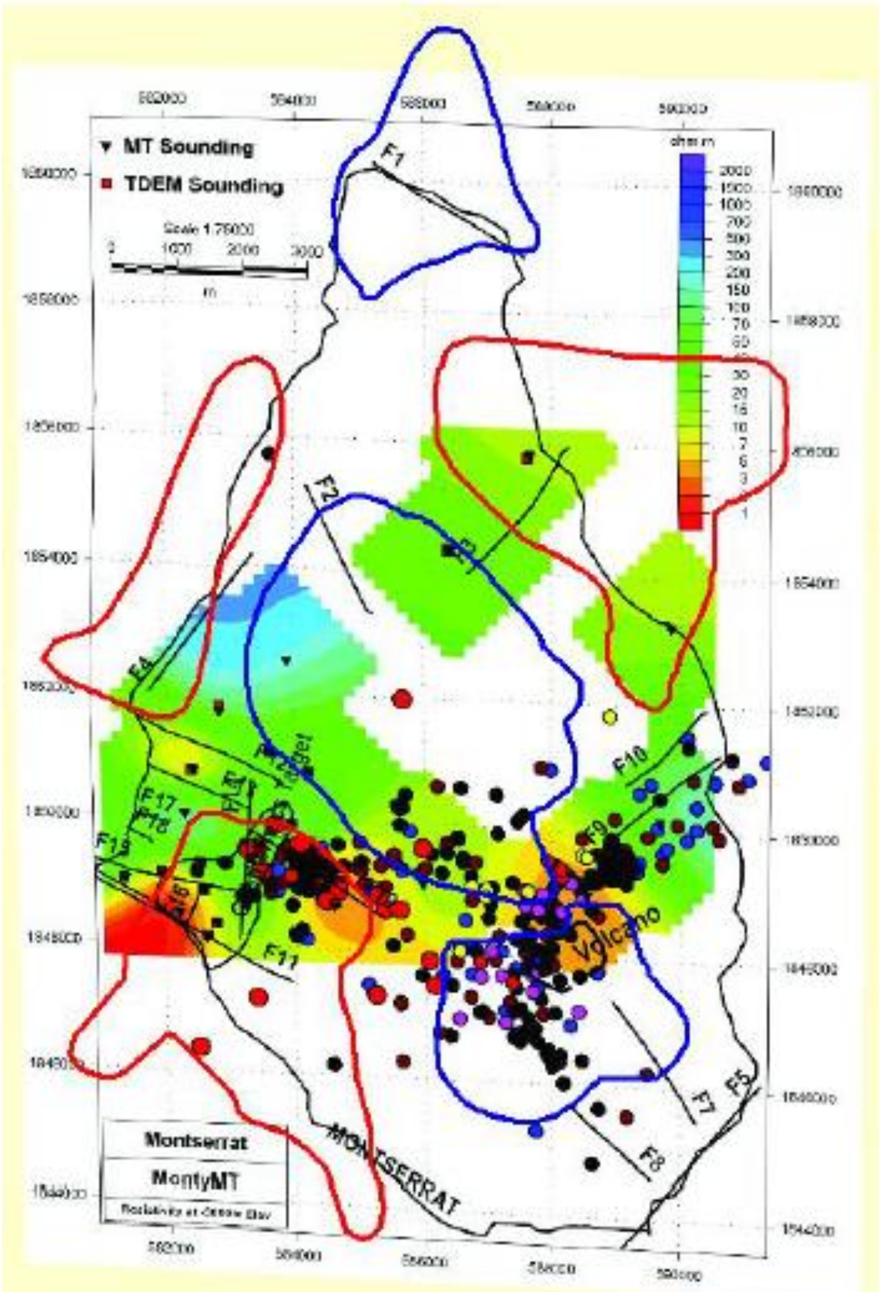


Figure 3.13: Integrated resistivity map at 3000 mbsl, seismic tomography map and MEQ locations. Red outlined areas enclose zones of low seismic velocity and blue outlined areas enclose areas of high seismic velocity. Anomalous seismic velocity zones occur at depths between 1000 and 3000 mbsl.

Many slides are based on the lectures prepared in collaboration to Prof. M. Pipan for the

ICS-UNIDO ICTP School on Geothermics, October 28, 2009

Other sources: lecture slide of UC Berkely
Slide show of AAPG (Schroeder's "The seismic method" at
http://www.aapg.org/slide_resources/schroeder/5/index.cfm