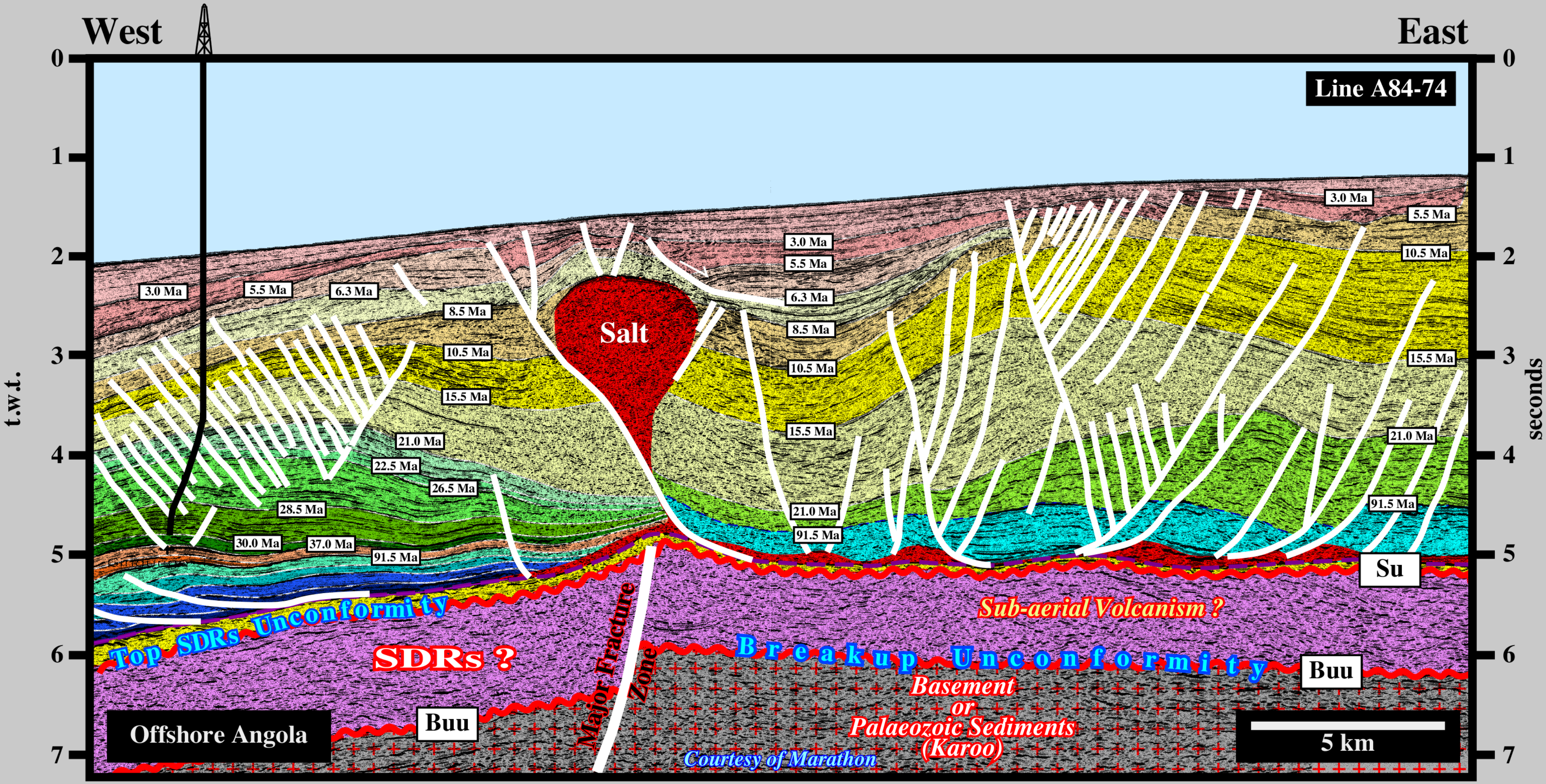
Seismic Stratigraphy Seminar



Caveat:

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C. Cramez, 2005

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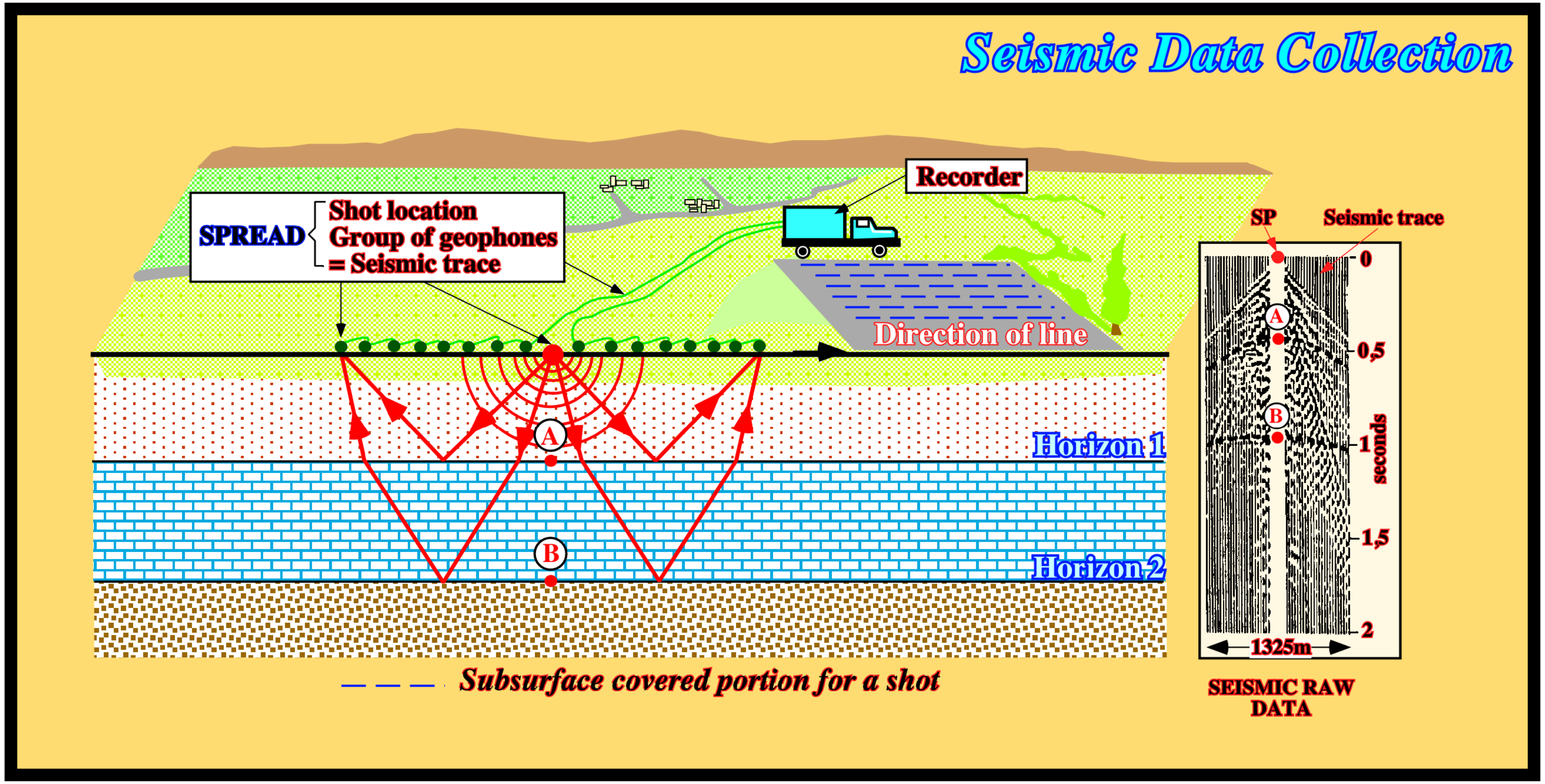
Volume I


Seismic Data Collection
Recorder
SPREAD
Shot location
Group of geophones
= Seismic trace
Direction of line
A
B
Horizon 1
Horizon 2
Subsurface covered portion for a shot
SP
Seismic trace
0
0,5
1
1,5
2
seconds
1325m
SEISMIC RAW DATA

Introduction

During my petroleum exploration career and academic activities, I have noticed that the approach to major problems in Earth sciences, and particularly in Exploration Geophysics, is still dependent on **Bacon's heritage.** He felt that the scientific approach in natural sciences should be inductive, and considered **Induction** as the demarcation criteria between science and pseudo-science, theology or metaphysics.

"Scientific theories, or hypotheses, should be established and justified by repeated observations"

This scientific approach still is strongly anchored in several oil companies. A lot of explorationists are still convinced they can make coherent and appropriate geological interpretations of seismic data without knowing Geology. Nevertheless, it is easy to show that seismic lines, such as the one illustrated on fig. 1, can only be correctly interpreted in geological terms when the interpreter knows the geology of the area where the line was shot. **"Theory precedes Observation"** (K. Popper, 1934), that is to say, an explorationist can only recognize on a seismic line, in the field, or on an electric log, what he knows. If he does not know what a thrust-fault, or an incised valley is, he can spend weeks looking at seismic lines or at outcrops, but the final result will be always the same:

"a geometrical description of more or less continuous, and well visible, reflections, or bedding planes, without understand how they fit in the regional and global setting"

Indeed, when a seismic line is shown to:

a) An explorationist trained in **seismic processing**, will see, besides the major reflections, multiples, diffractions, and coherent or incoherent noise patterns.
b) An explorationist, trained in **structural geology**, will see faulted blocks, growth-faults, anticlines, overthrusts, etc.
c) An explorationist, trained in **depositional processes**, will see prograding shelf edges, channels, submarine fans, etc.
d) An explorationist familiar with episodic **depositional concepts**, will see turbidites, point bars, tidal deposits, shoreface sands, etc.
e) An explorationist, knowing the basics **eustatic concept**s, will see sequences, downward shifts of coastal onlaps, lowstand deposits, highstand deposits etc.

Seismic Line

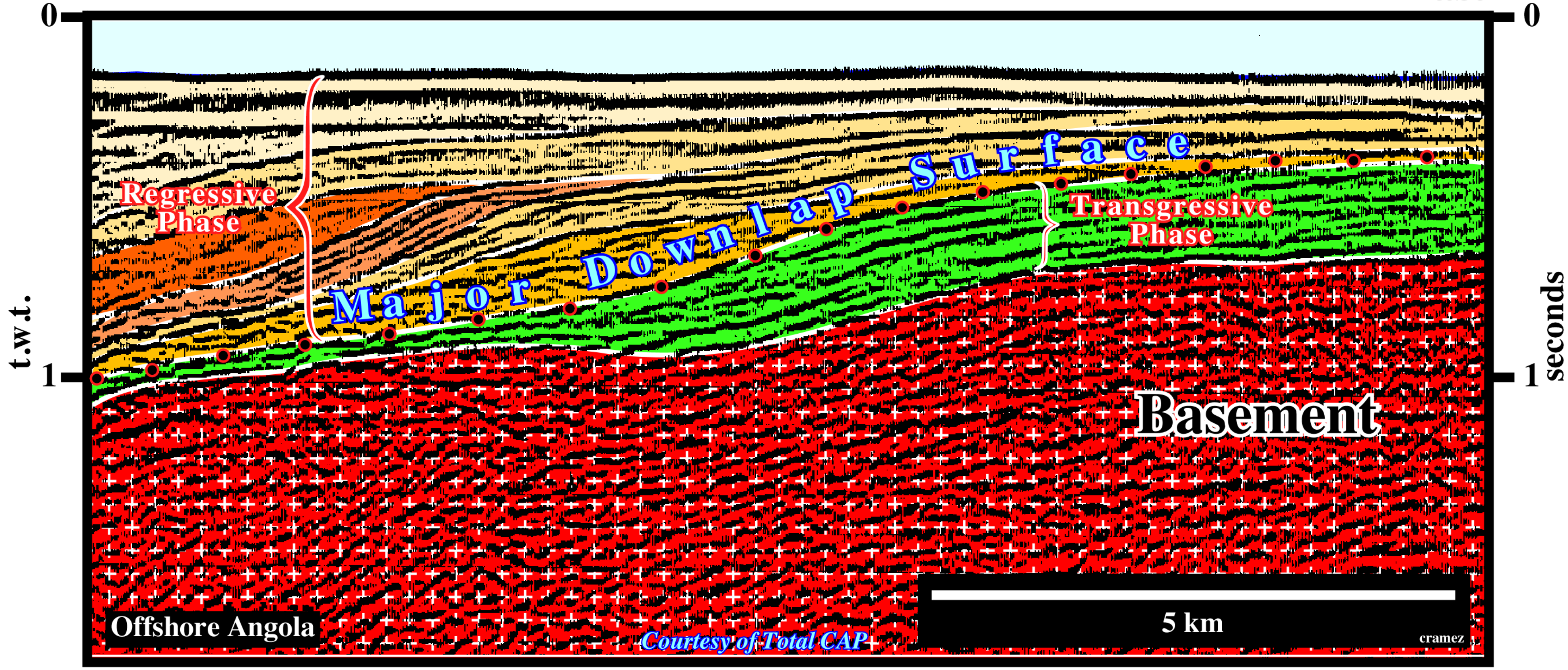


Fig. 1- This seismic line, shot on the conventional offshore (< 200m) of Angola, pictures the proximal area of the Kwanza basin. This offshore is composed by the stacking of different sedimentary basins. The basement, here with a granitic facies (Precambrian gneiss with garnets) outcrops a few kilometres eastward. Overlying Upper Jurassic / Lower Cretaceous rift-type basins (not present on this line), a Meso-Cenozoic Atlantic-type divergent margin was deposited. The margin is composed of a transgressive and regressive phase. The transgressive phase has backstepping geometry. The regressive phase has forestepping geometry. Hence, the interface between the transgressive and regressive phases corresponds to a major downlap surface. However, as illustrated, near the borders of the basin, the division of these sedimentary phases of the post-Pangaea continental encroachment stratigraphic cycle is subtler. Several unconformities, associated with relative sea level falls, can be recognized, primary in the regressive phase.

If you think I am exaggerating, you can make a quickly test using the sketch illustrated on fig. 2, which depicts more or less continuous seismic reflections (chronostratigraphic lines) taken from a seismic line, located in the offshore Mahakam (Indonesia).

So, what do you see in the sketch depicted on fig. 2?

If you are trained in sequential stratigraphy, it is possible you recognized something similar to what is illustrated on fig. 3, that is to say:

a) Cyclicity of the data;
b) Downward shifts of coastal onlaps;
c) Sequence boundaries (3rd order eustatic cycles);
d) Lowstand and highstand deposits;
e) Regression / transgression cycles (Genetic Stratigraphy);
f) Maximum flooding surfaces;
g) The most likely potential source-rocks;
h) The most likely potential sandstone reservoir-rocks;
i) The most likely potential seal-rocks;
j) The most likely potential stratigraphic traps, etc.

Probably, you will propose a final interpretation similar to that depicted on fig. 4, in which (i) **Sequential Stratigraphy** and (ii) **Eustatic Cycles** (that is to say, the sedimentary driving concepts controlling deposition) have been taken into account in the interpretation.

Summing up:

I may indeed be wrong, but I strongly think explorationists see what they know and what they have been trained to see. Indeed, when making observations, particularly on seismic data, it is necessary to understand the driving concepts controlling observations. Seismic interpreters must critically test their interpretations, present them to others, and listen to what they say. The same basic principles apply to well log and outcrop interpretations.

Observed Data

P.Vail, 1990 (unpublished)

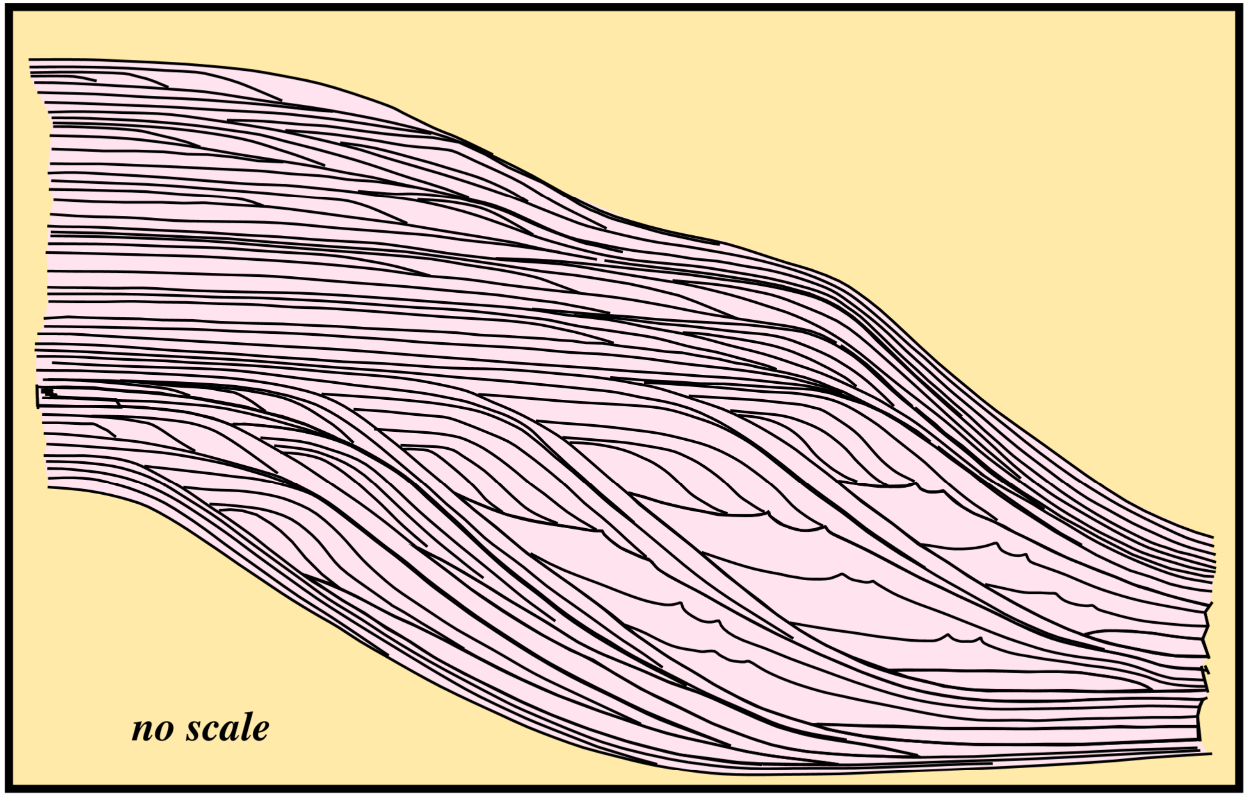


Fig. 2- On this sketch more or less continuous seismic reflectors taken from a seismic line shot on the offshore Kalimantan, in East Indonesia (Mahakam delta) are illustrated. Knowing the global and regional geological settings of this area, the major stratigraphic events of the non Atlantic-type divergent margin, that is to say, the uppermost sedimentary basin of the Makassar offshore, can be recognized using the geometrical relationships between the reflection terminations (see fig. 3).

Interpreted Data

P.Vail, 1990 (unpublished)

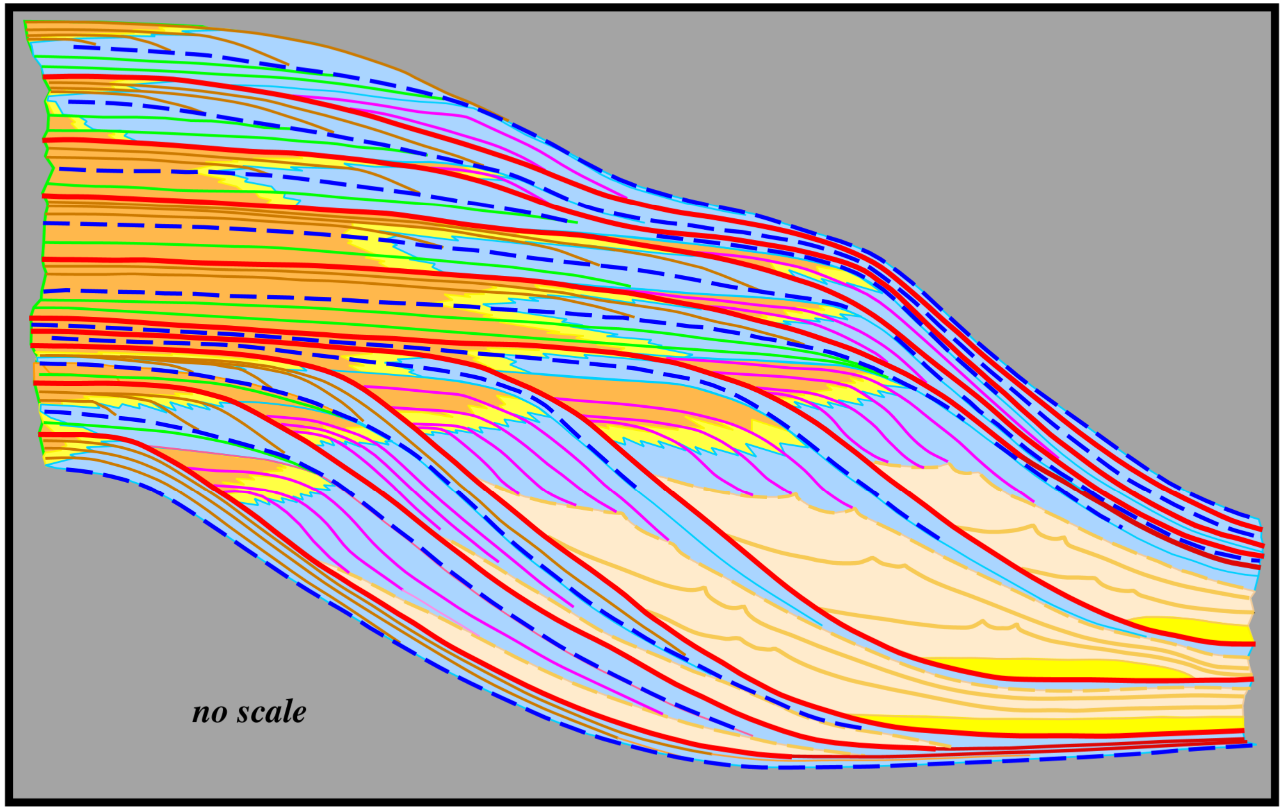


Fig.3- This figure depicts the observed data recorded by an explorationist trained in sequential stratigraphy and knowing the global and regional geological settings of the area where the seismic line was shot. Indeed, he recognized several relative sea level falls (RSLF) and associated unconformities (in red), as well as highstand and lowstand depositional systems. Seaward of the successive shelf-breaks, he identified basin floor fans, slope fans and lowstand prograding wedges. Similarly, he recognized time-intervals in which progradation was dominant (regression) and periods during which retrogradation (transgression) was paramount.

Final Interpretation

P.Vail, 1990 (unpublished)

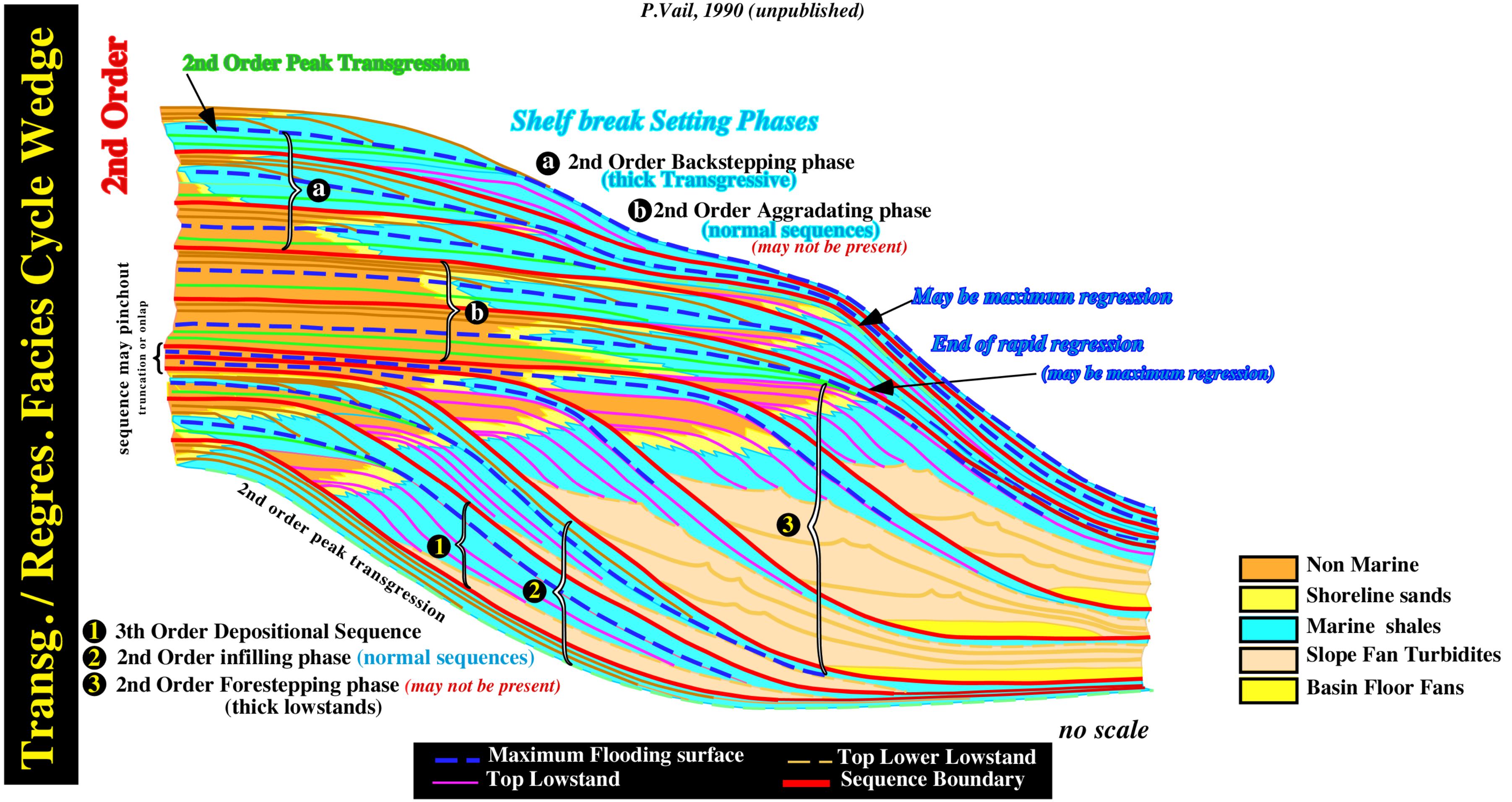


Fig. 4- The observed data (see fig. 2) can finally be interpreted in terms of sequential stratigraphy. The interpreter took into account not only the driving concepts of sequential stratigraphy and eustasy, but also the global and regional geological settings of the area. Indeed, Sedimentology and Tectonics are interlinked. In spite of the fact, that in this example tectonic knowledge is not required, it must be pointed out that Tectonics is also indispensable to perform coherent and likely seismic interpretations, that is to say, interpretations difficult to refute.

A) Geophysical Surveying

According to Nettleton (1976), any conceivable property or process which can be measured or carried out at above the surface and which is affected by the nature of rocks through a cover of hundreds to many thousands of feet of intervening rocks may be made the basis of a method of geophysical prospecting. Fundamentally, there are two main families of geophysical surveying (P. Kearey and M. Brooks, 1993):

(i) **Natural field methods**,
Utilize the gravitational, magnetic, electrical and electromagnetic fields of the Earth. They look for local perturbation in these naturally occurring fields that may be caused by concealed geological features.

(ii) **Artificial field methods,**
Involved the generation of local electrical or electromagnetic fields that may be used analogously to natural fields. In the most important single group of geophysical methods, the generation of seismic waves and their propagation velocities and transmission paths through the subsurfac, are mapped to provide information on the distribution of the geological boundaries at depth.

A wide range of physical surveying methods exists. For each method there is an operative physical property to which the results are sensitive:

a) **Seismic Method** measures the travel times of reflected or refracted seismic waves using as operative properties the density and elastic moduli, which determine the propagation velocity of seismic waves.

b) **Gravity Method** measures the spatial variations in the strength of the gravitation field of the Earth. The operative physical property is the density.

c) **Magnetic Method** measures the spatial variations in the strength of the magnetic field. The operative physical property is the magnetic susceptibility and remanence.

d) **Radar Method** measures the travel times of reflected radar pulses. The operative physical property is the dielectric constant.

In the majority of geophysical survey methods, geophysicists are mainly interested in **geophysical anomalies**, that is to say, local variations in the measured parameter, relative to some normal background value. Such variations are attributable to a localized subsurface zone of distinctive physical properties and possible geological importance.

Geophysical interpretation is ambiguous. P. Kearey and M. Brooks (1993) said:

> "If the internal structure and physical properties of the Earth were precisely known, the magnitude of any particular geophysical measurement taken at the Earth's surface could be predicted uniquely. Thus, for example, it would be possible to predict the travel time of a seismic wave reflected off any buried layer or to determine the value of the gravity or magnetic field at any surface location"

However, often, in geophysical surveying, the problem is the converse of the above, namely, to deduce some aspects of the Earth's internal structure on the basis of geophysical measurements taken at (or near to) the Earth's surface. The former type of problem is known as a **direct problem**, the latter as an **inverse problem**. Whereas direct problems are theoretically capable of unambiguous solutions, inverse problems suffer from an inherent ambiguity, or non-uniqueness, of conclusions that can be drawn. Let's see the examples proposed by P. Kearey and M. Brooks:

Direct problem:

The travel time of an echo-sounding is measured and converted into a water depth, multiplying the travel time by the velocity with which sound waves travel through water, i.e. 1500 ms^{-1}. Thus an echo time of 0.10s indicates a path length of 0.10 x 1500 = 150 m, or a water depth of 150/2 = 75 m, since the pulse travels down to the sea bed and back up to the transducer located in the ship.

Inverse problem:

Using the same principle, a simple seismic survey may be used to determine the depth of a buried geological interface (e.g. the top of a limestone layer). This would involve generating a seismic pulse at the Earth's surface and measuring the travel time of a pulse reflected back to the surface from the top of the limestone. However, the conversion of this travel time into a depth requires knowledge of the velocity with which the pulse travel along the reflection path and, unlike the velocity of sound in water, this information is generally not known. **If a velocity is assumed, a depth estimate can be derived but it represents only one of many possible solutions**.

Although the degree of uncertainty in geophysical interpretation can often be reduced to an acceptable level by the taking of additional field measurements, the problem of inherent ambiguity cannot be circumvented. The general problem is that significant differences from an actual subsurface geological situation may give rise to insignificant, or immeasurably small, differences in the quantities actually measured during a geophysical survey. Since a unique solution cannot, in general, be recovered from a set of field measurements, geophysical interpretation is concerned either **to determine properties of the subsurface that all possible solutions share**, or **to introduce assumptions to restrict the number of admissible solutions** (Parker, R. L., 1977).

Practically, all geophysical search for hydrocarbons depends on a very few basic physical principles:

(i) **Elastic waves**, (ii) **Magnetics**, (iii) **Gravity**,

which characterize the three main prospecting methods:

A) **Seismic methods**.
B) **Magnetic methods**.
C) **Gravimetric methods**.

Seismic methods are concerned with the measurement and analysis of waveforms that express the variation of some measurable quantity as a function of distance and time. The quantity of information, and in some cases, the complexity of data processing to which these waveforms are subjected is such that the processing can only be accomplished effectively and economically by digital computers. The two basic parameters of a digitizing system are:

1) **Sample Precision or Dynamic Range**:

The dynamic range, which is expressed in decibel (dB), is the expression of the ratio of the largest measurable amplitude to the smallest measurable amplitude in a sample function.

2) **Sampling Frequency**:

The sampling frequency is the number of sampling points in unit time or unit distance. Ex: if a waveform is sampled every two milliseconds (sampling interval), the sampling frequency is 500 samples per second or 500 Hz.

If the frequencies above the **Nyquist frequency*** are present in the sampled function, a serious form of distortion known as **aliasing** occurs. To overcome this problem, either the sampling frequency must be at least twice as high as the highest frequency component present in the sampled function, or the function must be passed through an anti-alias filter prior to digitalization.

Gravimetry and **Magnetics** are **potential** field methods:

They have their fundamentals in the mathematical theory of potential fields. So, gravitational or magnetic forces are, in a given direction, **the derivative**, or rate of change, in that direction of the gravitational or the magnetic potential.

Only the seismic method, and particularly seismic reflection and geological interpretation, will be reviewed in these notes. Magnetic and gravitational methods will be just briefly outlined here below.

B) Potential Field Methods

As these methods are based on the potential theory, they have certain elements in common. Nevertheless their applications in oil exploration are quite different:

(i) Measured gravity effects are caused by sources that may vary in depth from the grass roots down.

(ii) Sedimentary rocks, which are the ones in which generally hydrocarbon may occur, nearly always are so much less magnetic than the underlying basement (usually igneous or metamorphic rocks).

(iii) Magnetic effects are almost the same as if the sediments were not present.

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* Nyquist frequency is the frequency of half the sampling frequency.
Nyquist interval is the frequency range from zero to the Nyquist frequency.

Explorationists should not forget that these methods are deterministic, which imply an important epistemological limitation:

Gravimetric or magnetic maps can just falsify or corroborate geological models (indirect interpretation). They should not be used to make geological interpretations.

Gravity and magnetic processing sequences can be summarized as follows:

a) Pre-Processing

- Reading / Converting Field Tapes;
- Line Definition;
- Data Editing;
- Digitizing (if un-recordable or not recorded digitally);
- Positions, Shot-points, and Time (if acquired on a seismic operation).

b) Basic Processing

- **Meter Calibration, Base Constants and Drift;**

  Correction for instrumental drift is based on repeated readings at a base station at recorded times throughout the day.

- **Base Station Magnetic Observation and Diurnal;**

  The effects of diurnal variation may be removed in several ways. For magnetics (land) a method similar to gravimeter drift monitoring may be employed in which the magnetometer is read at a fixed base station periodically throughout the day.

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Magnetism

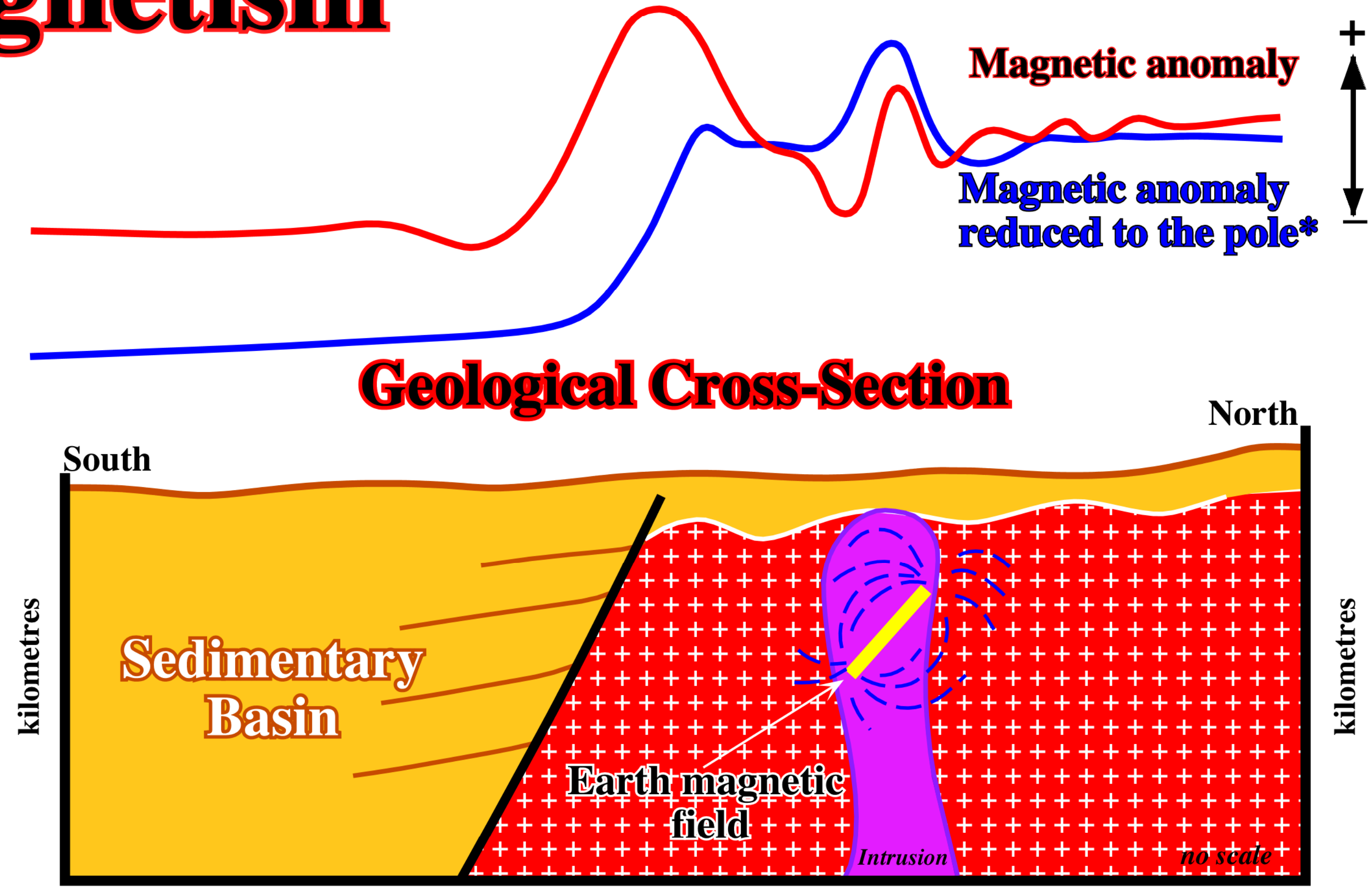


Fig. 5- This figure depicts the main principles of the magnetic method. A survey is made with a magnetometer on the ground or in the air. The survey yields local variations, or anomalies, in magnetic-field intensity. Then, the anomalies will be compared and interpreted, in relation to a geological model, as to the depth, size, shape, and magnetization of geologic features causing them.

* Reduction to the pole is a method of removing dependance on the angle of magnetic inclination. It converts data that have been recorded in the Earth's inclined magnetic field to what the data would have looked like if the magnetic field had been vertical.

Magnetometers do not drift and base readings are taken solely to correct for temporal variation in the measured field. Magnetic effects of external origin cause the geomagnetic field to vary on a daily basis to produce diurnal variations. Under normal conditions (quiet days), the diurnal variation is smooth and regular and has small amplitude, being at maximum in Polar Regions. Disturbing days are distinguished by far less regular diurnal variations and involve large, short-term disturbances in the geomagnetic field, with big amplitudes (magnetic storms).

- Intersection Determination;

- Misty Adjustments;

- Systematic Corrections
- Random Error Correction

- Profiling;

- Gridding and Contouring;

- General Reduction;

Before the results of gravity or magnetic surveys can be interpreted, it is necessary to correct them for all variations in the Earth‘s potential fields:

- International Gravity Formula;

A formula expressing theoretical gravity on the surface of a specified reference ellipsoid as a function of latitude.

- Earth’s Normal Magnetic Field;

The International Geomagnetic Reference Field (IGRF) defines the theoretical dipolar undisturbed magnetic field related to neck at any point on the Earth‘s surface. In magnetic surveying, the IGRF is used to remove from magnetic data those magnetic variations attributable to this theoretical field.

Gravimetry

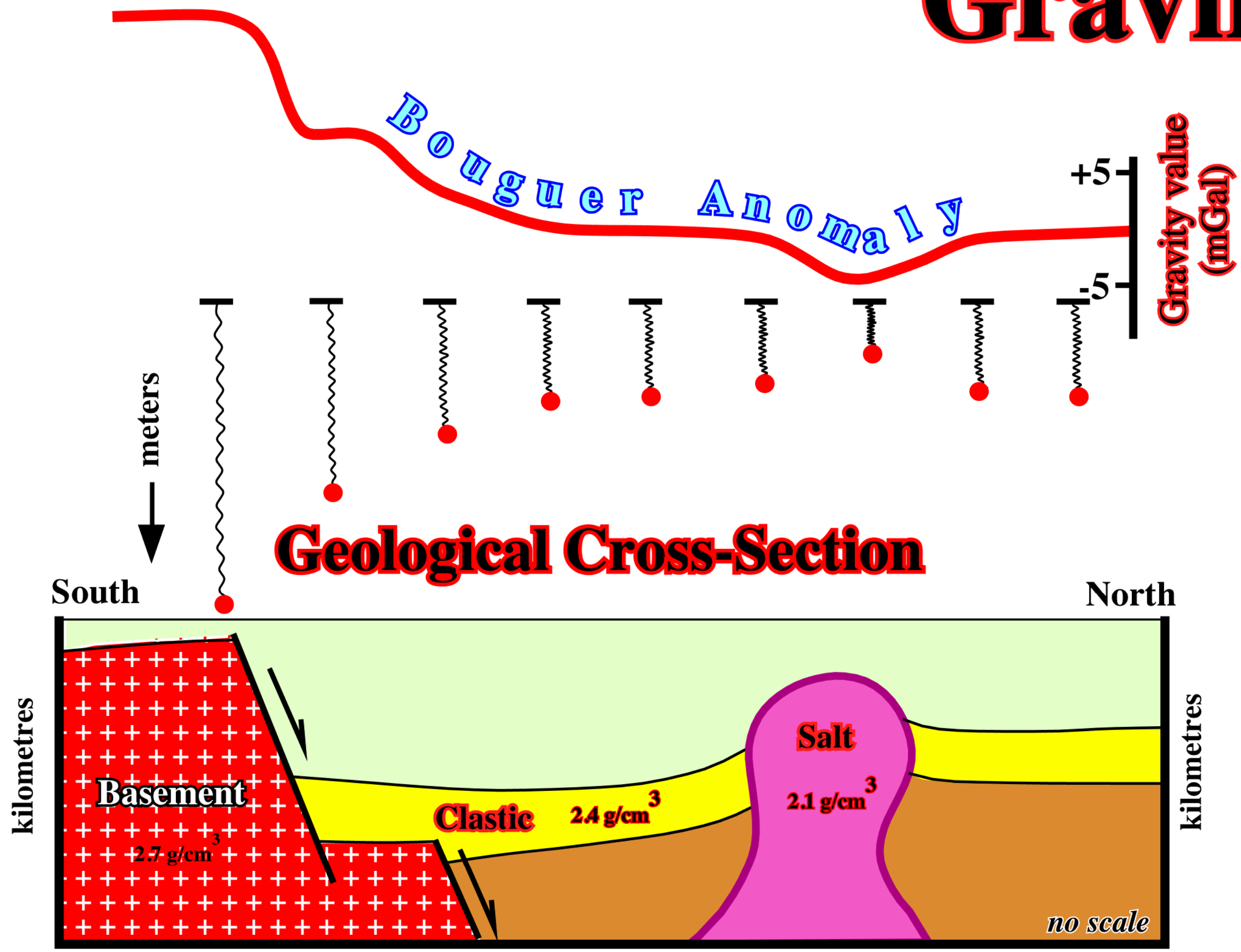


Fig. 6- The relatively low density of salt with respect to its surroundings renders the salt dome a zone of anomalously low mass. Earth‘s gravitational field is perturbed by subsurface mass distributions and the salt dome therefore gives rise to a gravity anomaly that is negative with respect to surrounding areas, as illustrated on the Bouguer anomaly. As gravimetry is a deterministic method, an *a priori* geological interpretation is required, which can be refuted or corroborated by the gravimetric data.

- Correction Sun / Moon motion;

- Eotovos Correction;

In gravity measurement, on a moving platform (ship or aircraft) a correction, for **centripetal acceleration** caused by east-west velocity over the surface of the rotating Earth, is necessary.

- Free Air Correction;

Correction corresponding to the natural decreasing of the field with elevation, that is to say, **the distance between observation point and the geoid**.

- Bouguer and Terrain Corrections;

The Bouguer correction is a correction made to gravity data for the **attraction of the rock between the station and the datum elevation** (commonly sea level). If the station is below the datum elevation, for the rock missing between the station and the datum, the Bouguer correction is 0.01276 ph mgal/ft, or 0.04185 ph mgal/m, where **p** is the specific density of the intervening rock and h is the difference in elevation between station and datum.

Terrain corrections should be applied if the actual topographic or bathymetric surface deviates significantly from the infinite Bouguer slab. For land and underwater stations, this correction **is positive** because both high areas above the station and low areas below it causes a lower gravity reading than would have been observed if the land were flat. For the sea stations over relatively deep water, a **negative correction** may be required because of the positive influence surrounding rocks above the station water depth.

Terrain correction can be made either manually or by computer by dividing the topography into compartments and summing the individual effects at each station. This requirement can add significantly to the cost of processing gravity data.

B.1- Magnetism

This method is based on measurements of small variations in the magnetic field:

- As most sedimentary rocks are nearly non-magnetic, all in-homogeneities in composition of basement rocks, or important topographic relief of the basement surface cause variations in the magnetic field.

- These variations can be measured by sensitive magnetometers at surface or, more commonly, by suitable instruments carried in an aircraft or behind a ship.

The measured variations in the magnetic field are interpreted in terms of the probable distribution of magnetic material below the surface, which in turn is the basis for inferences about the probable geological conditions (fig. 7).

Negative anomalies occur on the north sides of the buried magnetic masses in the northern hemisphere, and on the south side in the southern hemisphere. Maximum anomaly occurs at the poles and minimum anomaly at the equator.

The most important results of magnetic interpretation are:

(i) **Depth determination of the basement rocks, or the thickness of sediments;**

(ii) **Determination of local paleo-highs of the basement surface.**

The interpretation of magnetic anomalies is similar in its procedures and limitations to gravity interpretation as both techniques utilize natural potential fields based on inverse square laws of attraction:

The force **F** between two magnetic poles strengths **A** and **B** separated by a distance **r** is given by:

$$F = u\ AB/4piu'r^2$$

where, **u** is **the magnetic permeability of vacuum**, and where **u'** is **the relative magnetic permeability of the medium separating the poles**.

Negative Magnetic Anomaly

(Salt Dome)

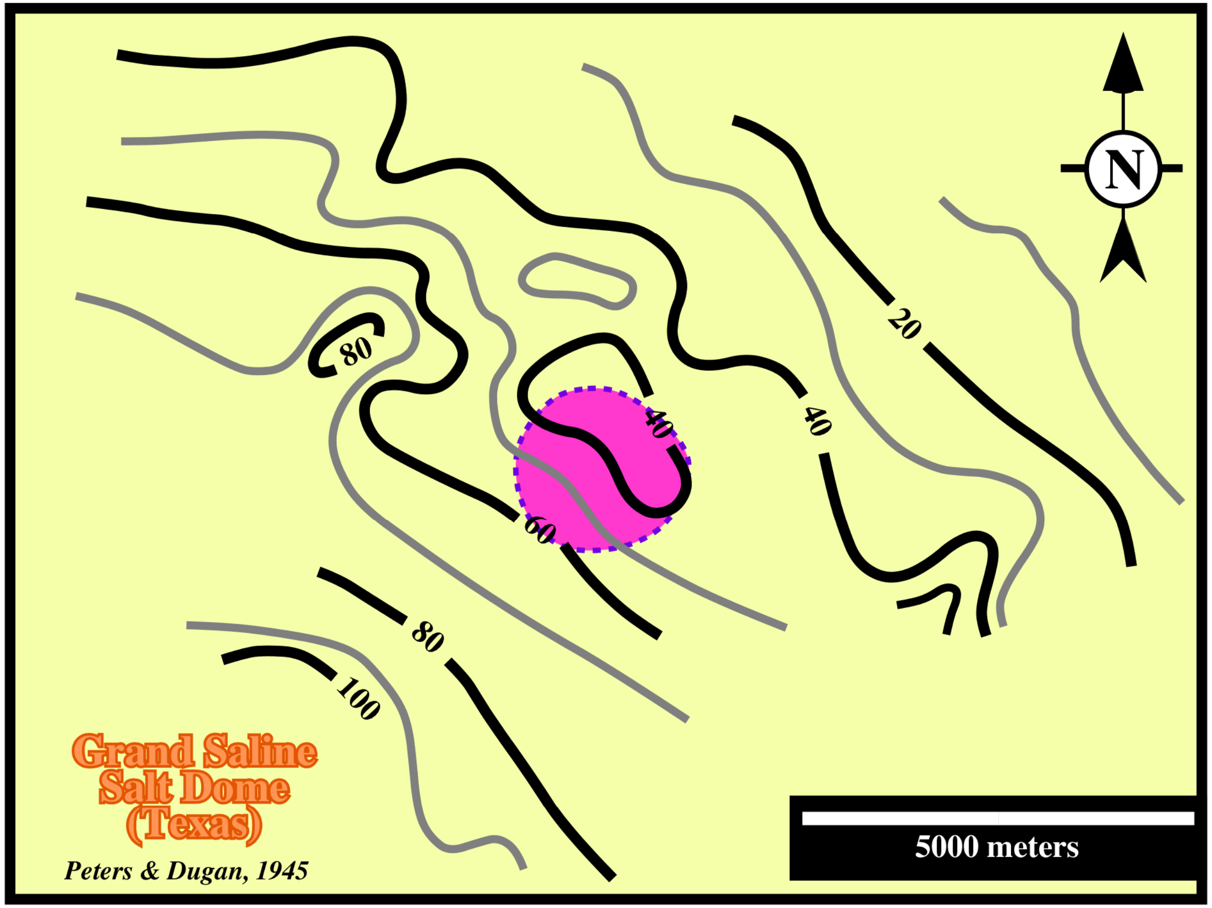


Fig. 7- The negative magnetic susceptibility of salt causes a local decrease in the strength of the Earth's magnetic field in the vicinity of a salt dome. Readings have been corrected for large-scale variations of the magnetic field with latitude, longitude and time. The contours reflect only those variations resulting from variations in the magnetic properties of the subsurface. On this map, as expected, the salt dome (in purple) creates a negative anomaly, although the magnetic low is displaced slightly from the centre of the dome (see also figs. 15 and 16).

There are several differences which increase the complexity of magnetic interpretation:

a) The gravity anomaly of a causative body is entirely positive or negative, depending on whether the body is more or less dense than its surroundings.

b) The magnetic anomaly of a finite body invariably contains positive and negative elements arising from the dipolar nature of magnetism.

c) The density is a scalar and the intensity of magnetization is a vector.

d) The direction of magnetization in a body closely controls the shape of its magnetic anomaly.

For the above reasons, magnetic anomalies are often much less closely related to the shape of the causative body than are gravity anomalies:

"Bodies of identical shape can give rise to very different magnetic anomalies"

As in other potential methods, the interpretation can be:

(i) **Direct** or
(ii) **Inverse** (see page 12).

Limiting depth is the most important parameter derived by direct interpretation:

- It may be deduced from magnetic anomalies by making use of their property of decaying rapidly with the distance.

- The inverse or indirect interpretations of magnetic anomalies are made to match the observed anomaly with that calculated for a model by iterative adjustments to the model.

The sequence of a magnetic interpretation can be summarized as follows:

a) Magnetic Anomaly (fig. 8):

Magnetic Anomaly

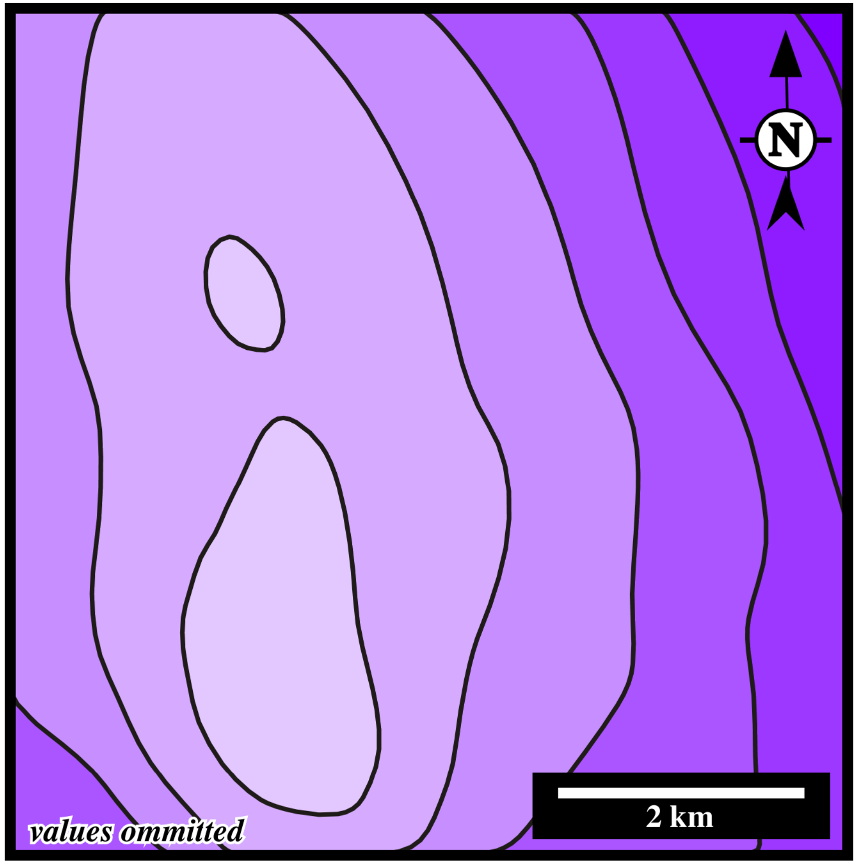


Fig. 8- This map illustrates a magnetic anomaly, which represents the intensity of the Earth's Magnetic field corrected for regional field (dipole effect) and diurnal (HF variations) effects. Magnetic anomalies are the difference between observed and corresponding computed values or the difference from the general surrounding values. Such differences are often induced by geological features.

About 90% of the Earth's field can be represented by the field of a theoretical magnetic dipole at the centre of the Earth inclined at about 11°5 to the axis the rotation:

(i) The magnetic moment of this fictitious **geocentric dipole** can be calculated from the observed field.

(ii) If this dipole is subtracted from the observed magnetic field, the residual field can be approximated by the effects of a second smaller dipole.

(iii) The process can be continued by fitting dipoles of ever decreasing moment until the observed geomagnetic field is simulated to any required degree of accuracy.

b) RTP of Magnetics (fig. 9):

Reduction to the pole involves the conversion of anomalies into their equivalent form at the north magnetic pole.

This process usually simplifies the magnetic anomalies, as the ambient field is then vertical and bodies with magnetizations which are solely induced, produce anomalies that are easy.

The existence of remnant magnetization, however, commonly prevents reduction to the pole from producing the desired simplification in the resultant pattern of magnetic anomalies.

c) RTE of Magnetics (fig. 10)

The reduction to the equator

In the northern hemisphere, the magnetic field generally dips downward the north and becomes vertical at the north magnetic pole. In the south hemisphere the dip is generally upward toward the north.

The line of zero inclination approximates the geographic equator, and is know as the **magnetic equator**.

RTP of Magnetics

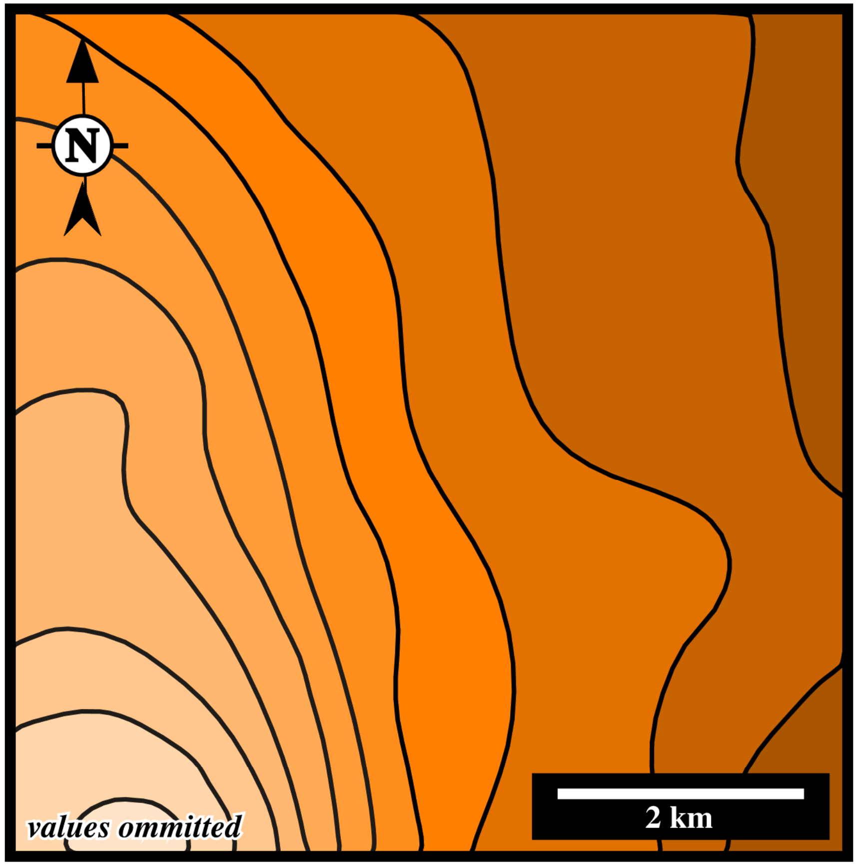


Fig. 9- A reduction to the pole (RTP) map of magnetics, as the one illustrated above, corresponds to the conversion of the anomalies into their equivalent form at the north magnetic pole. This process usually simplifies the magnetic anomalies (fig. 8) as the ambient field is then vertical and bodies with magnetizations, which are solely induced,produce anomalies that are axisymmetric. However, as said previously, the existence of remnant magnetization often prevents reduction to the pole.

RTE of Magnetics

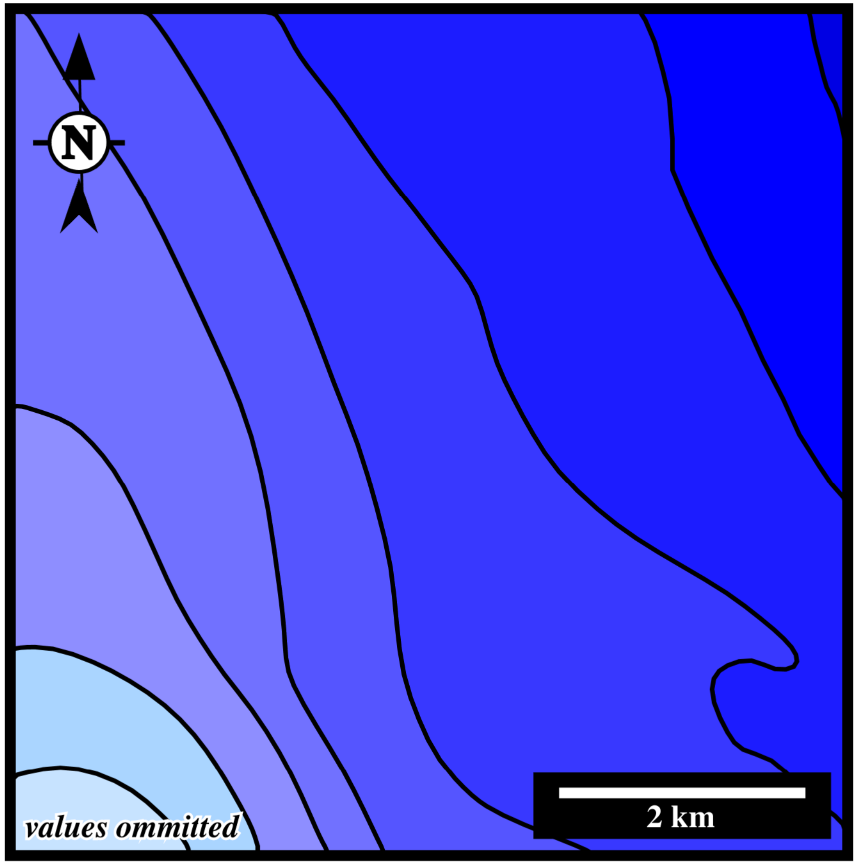


Fig. 10- A reduction to the equator (RTE) map of magnetics, as the one illustrated above, represents what the data would have looked like if the magnetic field had been horizontal (zero inclination). Indeed, in the northern hemisphere, the magnetic field generally dips downward toward the north pole, while in the southern hemisphere, the dip is generally upward toward the north. Hence, the advantages of a RTE map are evident. Compare this map with the RTP (fig. 9) and magnetic anomaly map (fig. 8).

d) SVD of RTP (fig. 11)

In geophysics, **derivative maps** are maps of one of the derivatives of a potential field, such as the Earth's gravity or magnetics. Generally, it is usually of the second vertical derivative, or second-derivative map. So, the derivative of a function, as the reduction to the pole, expresses the rate of change of that function. Indeed, on the graph of the curve

$$y = f(x)$$

the derivative at a given point **x** is equal to the slope of the tangent line at the point [x, f(x)]. As illustrated on fig. 11, a derivative map enhances the anomalies, which allows a finer location of the magnetic bodies.

e) SVD of RTE (fig. 12)

Second vertical derivative of the reduction to the equator maps, as that illustrated on fig. 12 are often made to facilitate the recognition of subtle magnetic anomalies.

f) Magnetic Interpretation

In magnetic interpretations, the problem of ambiguity is the same as for gravity, that is to say, the same inverse problem is encountered. All external controls on the nature and form of the causative body must be employed to reduce the ambiguity. In other words, **the ame magnetic anomaly can be induced by different sources**. Magnetic surveys are used in the early stage of petroleum exploration. Indeed:

(i) Magnetic anomaly maps show the overall geological grain of an area. The orientation of basement highs and lows is generally apparent.
(ii) Faults may show up (close spacing or abrupt change of contours).
(iii) Sometimes, magnetic maps are used to differentiate basement (igneous and metamorphic rocks devoid of porosity) from the sedimentary cover that may be prospective. However, such a differentiation is just possible when there is a sharp contrast between the magnetic susceptibility of the basement and cover and where this contrast is laterally persistent.
(iv) Magnetic anomaly maps are also useful in petroleum exploration for indicating the presence of igneous plugs, intrusive rocks, or lava flows, i.e. areas normally avoided in the search for hydrocarbons.

SVD of RTP

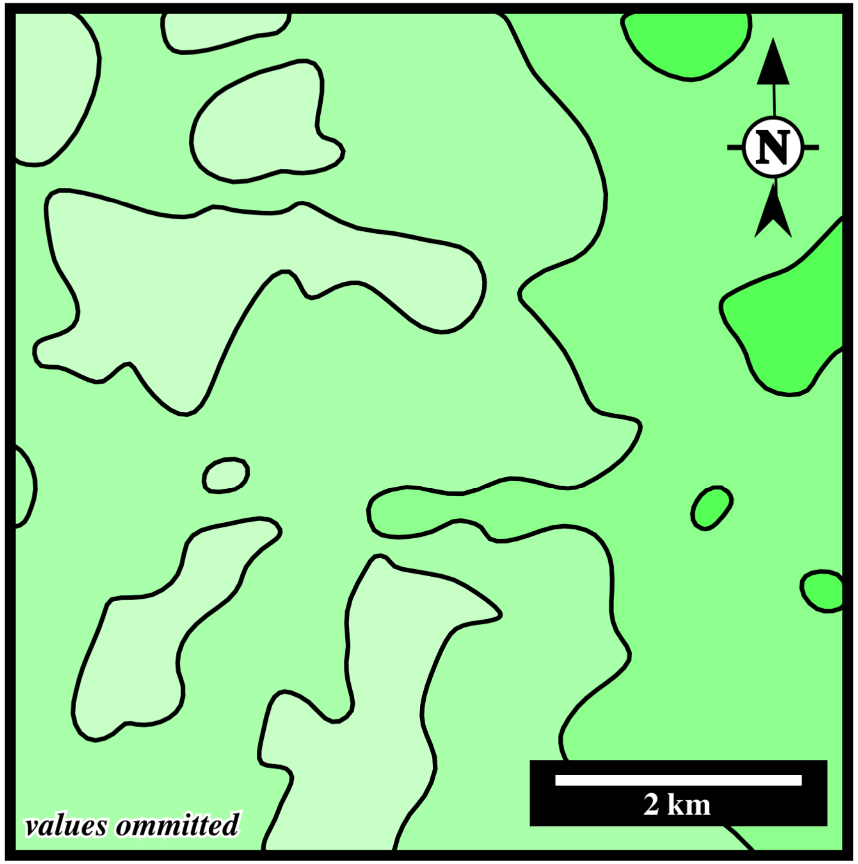


Fig. 11- As illustrated above, the second vertical derivative (SVD) of the reduction to the pole (RTP) map enhances subtle magnetic anomalies, which can later be corroborated or not by geological data. Enhancement of classic potential fields allows a better localization of the sources. Notice the derivative of a curve is its tangent. During the night, when you drive your car in a mountainous road, the light of the car gives the derivative of the road, that is to say, its inclination.

C.Cramez
Switzerland

SVD of RTE

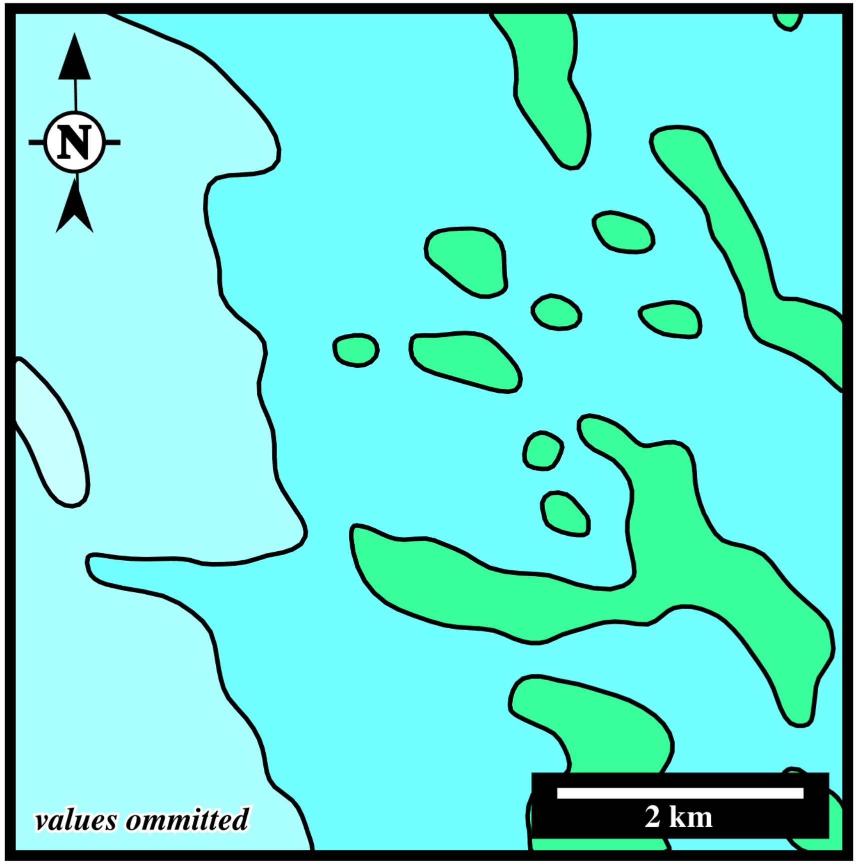


Fig. 12- This map represents the second vertical derivative (SVD) of the reduction to the equator (RTE) of the magnetic anomaly (see fig. 8), which by enhancing the potential field switch order a better localization of the magnetic source. To understand such enhancements suppose a long quite flat road, in which several bumpers were put in place by the local police. When driving during the daytime, the bumpers, when not painted, are difficult to locate. However, when driving during the night, they are easily located by the abrupt changes of the lights of the car moving in opposite direction.

Geological Model

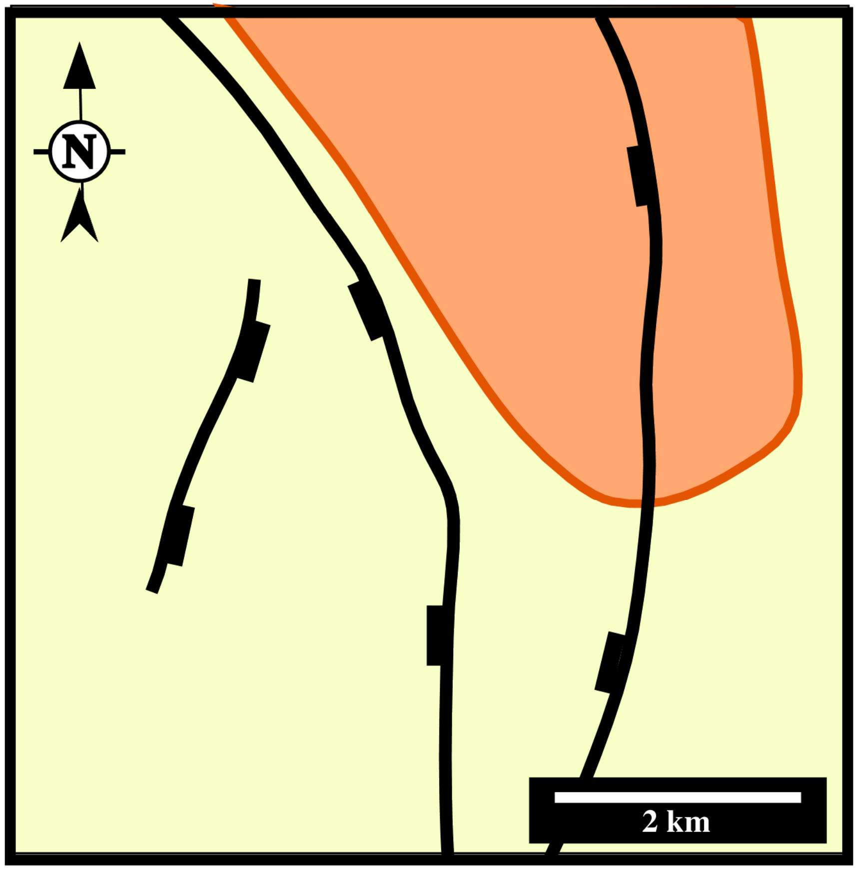


Fig. 13- As illustrated above, a monocline geological model dipping westward with a small sedimentary trough, striking North-South and located in the western part of the map, is corroborated by the previous magnetic maps (fig. 8 to 12). Significant normal faults striking roughly north-south, seem to have lengthened the sediments. A magnetic source is likely in the north-eastern area. The proposed geological model must be tested by gravimetric and finally by seismic and subsurface data.

(v) Seismically delineated “reef” have often been drilled and finally interpreted as igneous intrusions or volcanic plugs. A quick check of a magnetic map would indicate the presence of a magnetic anomaly and suggest an igneous intrusion rather than a reef.

In conclusion:

Magnetic surveys are a quick and cost effective way of defining broad basin architecture. Though, they can seldom be used to located drillable petroleum prospects. They can sometimes differentiate phony prospects and thus prevent geo-books from taking place.

B.2- Gravimetry

The basis of the gravity method is the **Law of Gravitation**:

It states that the force of attraction **F** between two masses m_1 and m_2, whose dimensions are small with respect to the distance **r** between them, is given by

$$F = G(m_1 \times m_2) / r^2$$

where **G** is the Gravitational Constant.

Considering the gravitational attraction of a spherical non-rotating, homogeneous Earth of mass **M** and a radius **R** on a small mass **m** on its surface, it is relatively simple to show that the mass of a sphere acts as though it was concentrated at the centre of the sphere. Using **M**, **R** and **m** on the previous equation, the force of attraction **F** is given by

$$F = (GM/R^2)\, m = mg$$

Bouguer Anomaly

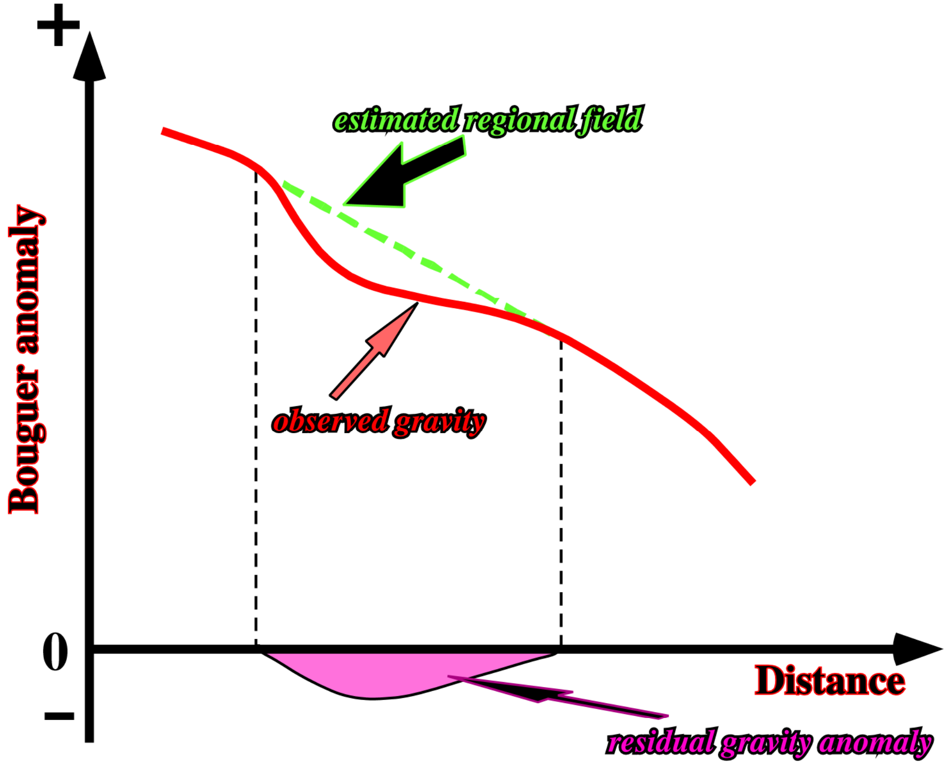


Fig. 14- The Bouguer anomaly (BA) corresponds roughly to the difference between the estimated regional gravity field and the observed gravity. In fact, this difference must be corrected by free-air correction (FAC), the Bouguer correction (BA), and the terrain correction (TC) or Eötvös correction (EC) when the gravity measurements are taken in a moving vehicle. Residual gravity anomalies are conventionally displayed on profiles or as isogal maps.

Force is related to **mass** by acceleration and the term

$$g = GM/R^2$$

is known as the **gravitational acceleration** or, simply, **gravity**.

- The mean value of gravity at the Earth's surface is about 9.80 m /s.

- Variations in gravity caused by density variations in the surface are expressed in micrometer per second (gu).

The gravitational field is most usefully defined in terms of gravitational potential:

$$U = GM/r$$

Whereas the gravitational acceleration **g** is a vector quantity, having both magnitude and direction (vertical downward), the gravitational potential **U** is scalar, having magnitude only. Small differences or distortions in that field from point to point over the surface of the Earth are caused by any lateral variation in the distribution of rocks in the Earth's crust:

- If the Earth's subsurface was of uniform density (spherical non-rotating, homogeneous Earth of mass M), the Earth's gravitational field, after the application of certain corrections, **would everywhere be constant**.

- Any lateral density variation associated with a change of subsurface geology results in a local deviation in the gravitational field.

- Local deviations from the otherwise constant gravitational field are referred to as **gravity anomalies**.

Geologic movements, as salt flowage or faulting, induce lateral density variations. A gravity anomaly calculated after corrections for:

(i) **Latitude**, (ii) **Elevation**, and (iii) **Terrain**

is known as **Bouguer anomaly** (fig. 14).

Gravity Anomaly

(Over a Salt Dome)

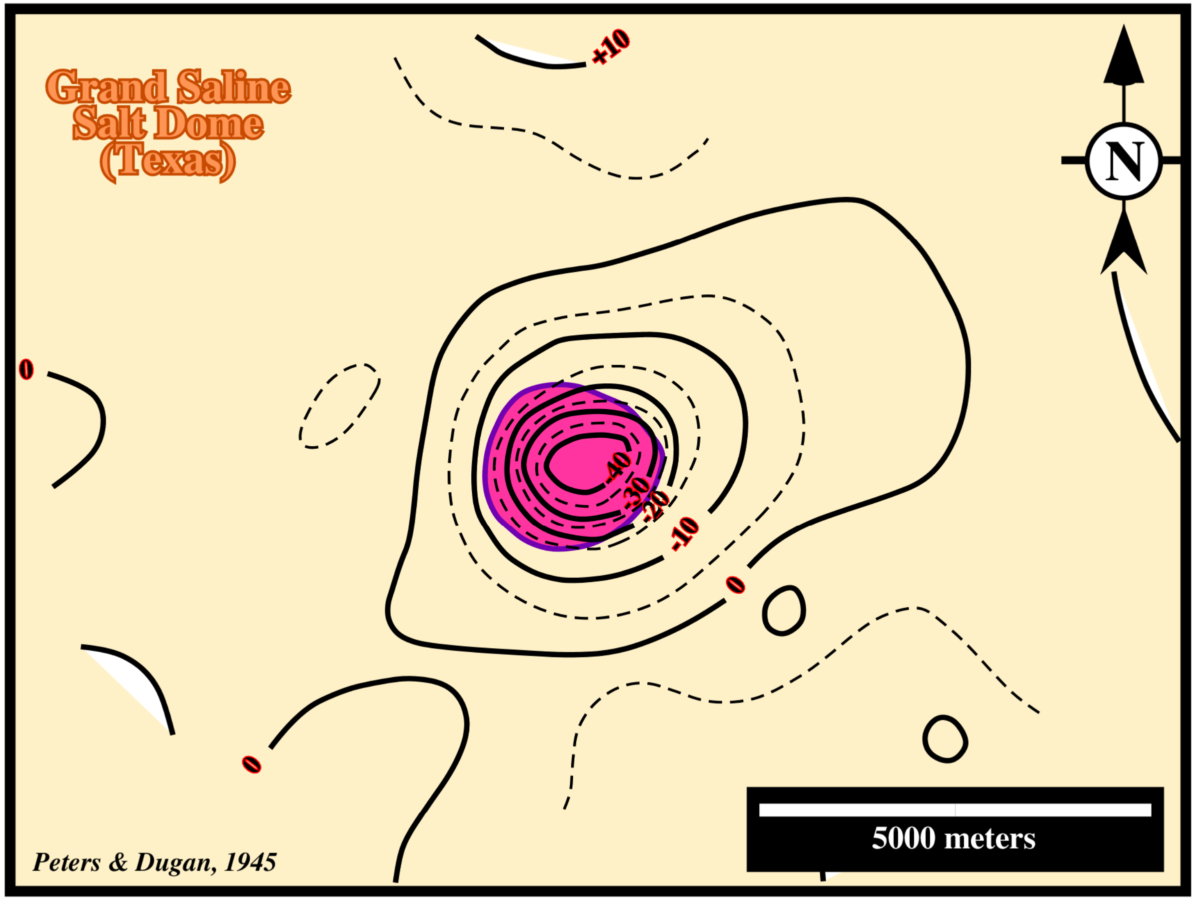


Fig. 15- This map illustrates the negative gravity anomaly over the Grand Saline Salt Dome (see magnetic anomaly on fig. 7). The gravitational readings have been corrected for effects resulting from (i) **Earth's rotation**, (ii) **Irregular surface relief** and (iii) **Regional geology**. The contours reflect just variations in shallow density structures of the area induced by local geology. As depicted in fig. 6, the low density of the salt, generally between 2.15 and 2.17 g/cm³, induces a negative gravity anomaly. A large numbethe Caspian Sea.

Regional and residual gravity anomalies must be individualized from the observed Bouguer anomaly:

(i) **Bouguer anomaly fields** (figs. 14 and 15) are often characterized by a broad, gently varying, regional anomaly on which may be superimposed higher wave number local anomalies.

(ii) Usually, in gravity surveying, **local anomalies** are of prime interest.

(iii) The first step is the **removal of the regional field** to isolate the **residual anomalies**.

(iv) Removal can be performed **graphically** by sketching in a linear or curvilinear field by eye.

(v) Graphic methods can be biased by the interpreter, but this is not necessarily disadvantageous as **geological knowledge can be incorporated** into the selection of the regional field.

(vi) Several **analytical methods** of regional field analysis are available (trend surface analysis, low-pass filtering, etc.).

Gravity measured at a fixed location, **varies with time** because of periodic variation in the gravitational effects of the Sun and Moon associated with their orbital motions. Correction must be made for this variation in a high precision survey.

- Gravitational effects cause the **shape of the solid Earth** to vary in much the same way that the celestial attractions cause tides in the sea.

- **Solid Earth tides** are considerably smaller than oceanic tides and lag farther behind the lunar motion.

- Solid Earth tides cause **the elevation of an observation point** to be altered by a few centimetres and thus vary its distance from the center of mass of the Earth.

As with other geophysical methods, explorationists should not forget the epistemological limitation of gravimetry. Indeed Gravimetry, as well as Magnetism, is a deterministic geophysical method. Therefore, fundamentally

"an anomaly map corroborates or refutes a geological interpretation"

Salt Dome

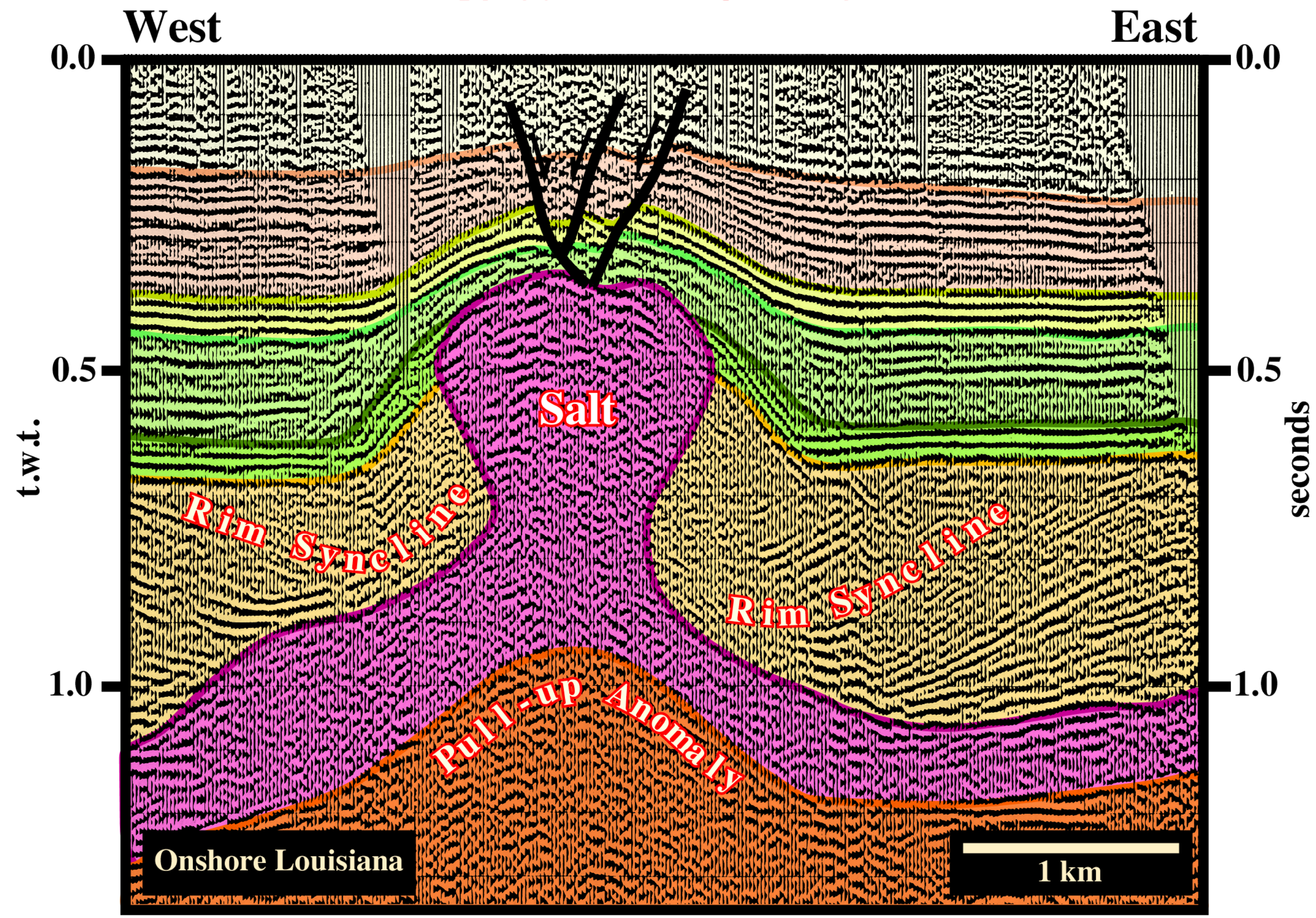


Fig. 16- The magnetic and gravity anomalies illustrated on figs. 7 and 15 were performed over a salt dome that later was completely identified by this seismic line (Grand Saline Salt Dome, Texas, USA). Potential methods can roughly put in evidence the exact location and geometry of salt domes. They do not allow an exhaustive understanding of the geometry of the salt structures. Nevertheless, they can be used to test the coherence of the geological interpretations. In this particular example, the bulb and stem of the salt dome are quite evident as well as the associated rim synclines.

It is rare than a gravimetric map allows a direct accurate geological interpretation. In addition, since the gravity is acceleration, its measurement should simply involve determinations of length and time. However, the measurement of an absolute value of gravity is extremely difficult and requires complex apparatus and a lengthy period of observation. Interpretation sequence of gravimetric data can be summarized as follows:

a) Bouguer Gravity (fig.17)

Corrections for the differing elevations of the gravity stations is made in three parts:

1) The free-air correction (FAC),

It corrects the decrease in gravity with height in free air resulting from increased distance from the centre of the Earth, according to Newton's Law.

2) The Bouguer correction (BC),

It removes the gravitational effect of the rock present between the observation point and datum.

3) The terrain correction (TC),

It takes into account the topographic relief in the vicinity of the gravity station. This correction is always positive.

b) Regional Gravity (fig.18)

The estimated regional field is calculated using the observed gravity as shown on fig. 14.

c) Residual Gravity (fig. 19)

To isolate the residual anomalies it is necessary to remove the regional field:

- This can be made graphically, but such a method is often biased by interpreters.
- Several analytical methods of regional field analysis are available and include trend surface analysis (fitting a polynomial to the observed data) and low-pass filtering.

Bouguer Gravity

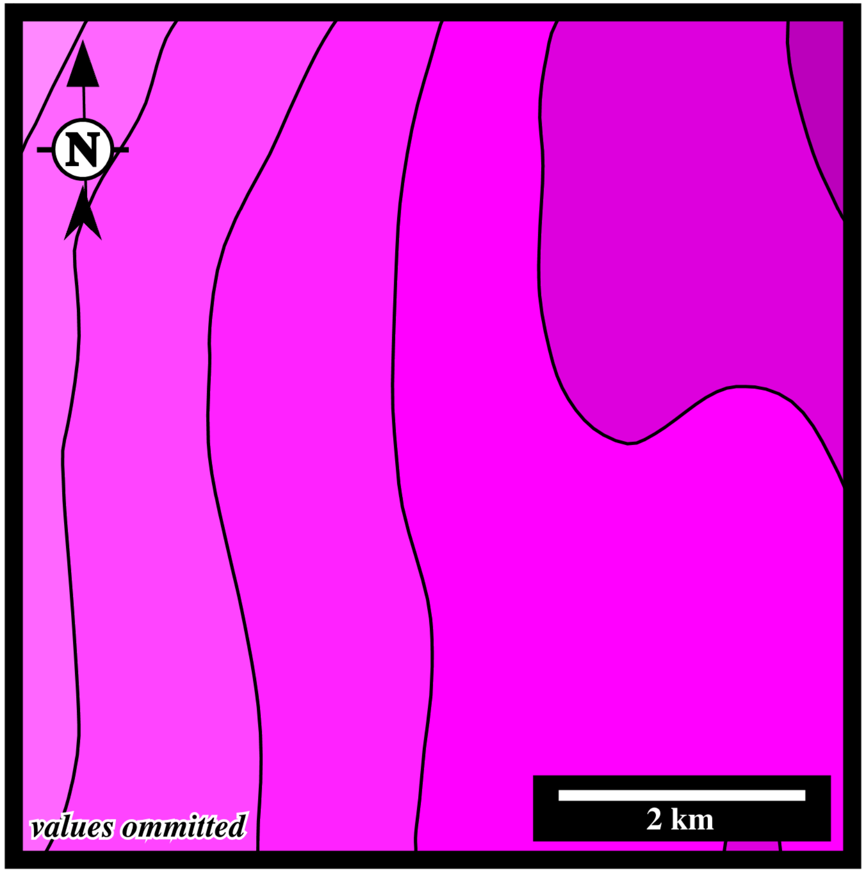


Fig. 17- This map illustrates the Bouguer Gravity of the area covered by the magnetic anomaly depicted in fig. 8. It represents the gravity anomaly corrected for topographic and elevation effects.

Regional Gravity

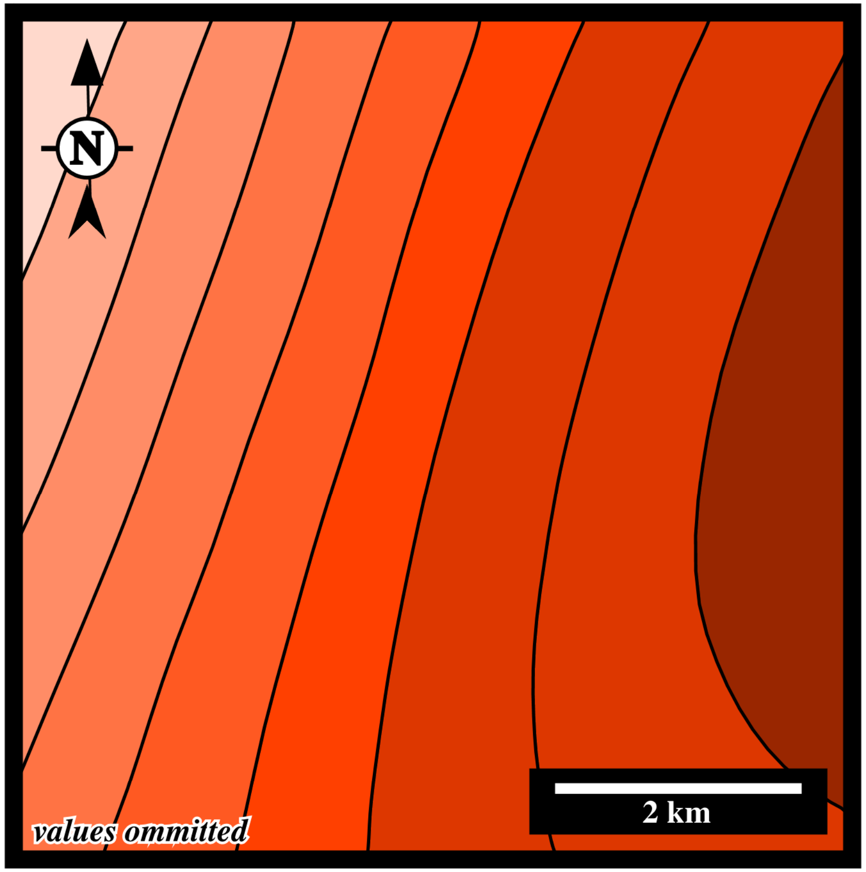


Fig. 18- This map illustrates the Regional Gravity. It represents the long wave-length of the gravimetric anomaly associated with deeper sources.

Residual Gravity

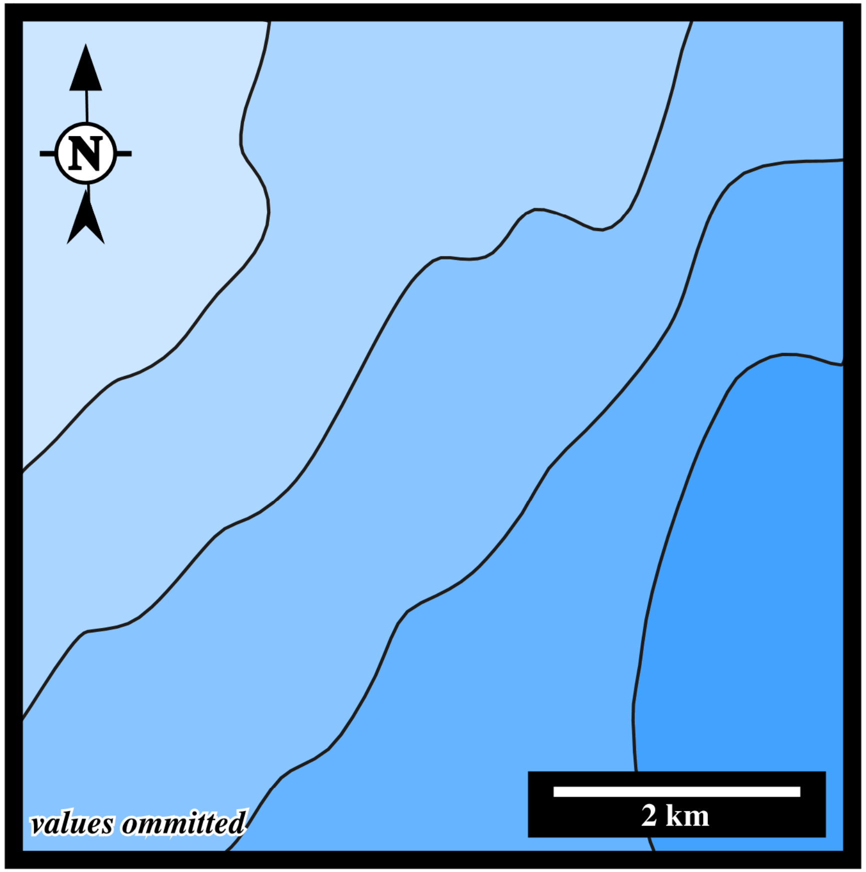


Fig. 19- This Residual Gravity represents the short wavelengths of the anomaly related to shallower sources. In other words, it represents the gravity anomalies when the regional field is removed.

d) SVD of Bouguer

As for magnetics, gravimetric anomalies can be enhanced by the **second vertical derivative** of Bouguer anomaly maps (fig. 20). These maps are necessary since limiting depth refers to the maximum depth at which the top of a body could lie and still produce an observed gravity anomaly. Actually,

- Gravity anomalies decay with the **inverse square of the distance** from their source.
- Anomalies caused by deep structures are of **lower amplitude and greater extent** than those caused by shallow sources.
- The waves number-amplitude relationship to depth may be quantified to compute the maximum depth at which the top of anomalous body could be situated.

e) SVD of Residual

As for Bouguer anomaly, **the second vertical derivative map** of the residual gravity (fig. 21) can be quite useful

f) Gravity Interpretation

Gravity interpretation (fig. 1.22), as in magnetics, can be done by **direct and inverse methods** of interpretation. Direct interpretation provides, directly from the gravity anomalies, information on the anomalous body which are largely independent of the true shape of body. Various methods are used:

(i) Half-width method,
(ii) Gradient-amplitude ratio method,
(iii) Second derivative methods.

In indirect or inverse interpretation, the causative body of a gravity anomaly is simulated by a model whose theoretical anomaly can be computed, and the shape of the model is altered until the computed anomaly closely matches the observed anomaly. Because of the inverse problem, this model will not be a unique interpretation, but **ambiguity can be decreased** by using other constraints on the nature and form of the anomalous body:

A simple approach to indirect interpretation is the comparison of the observed anomaly with the anomaly computed for certain standard geometrical shapes whose size, position, form and density contrast are altered to improve the fit.

SVD of Bouguer

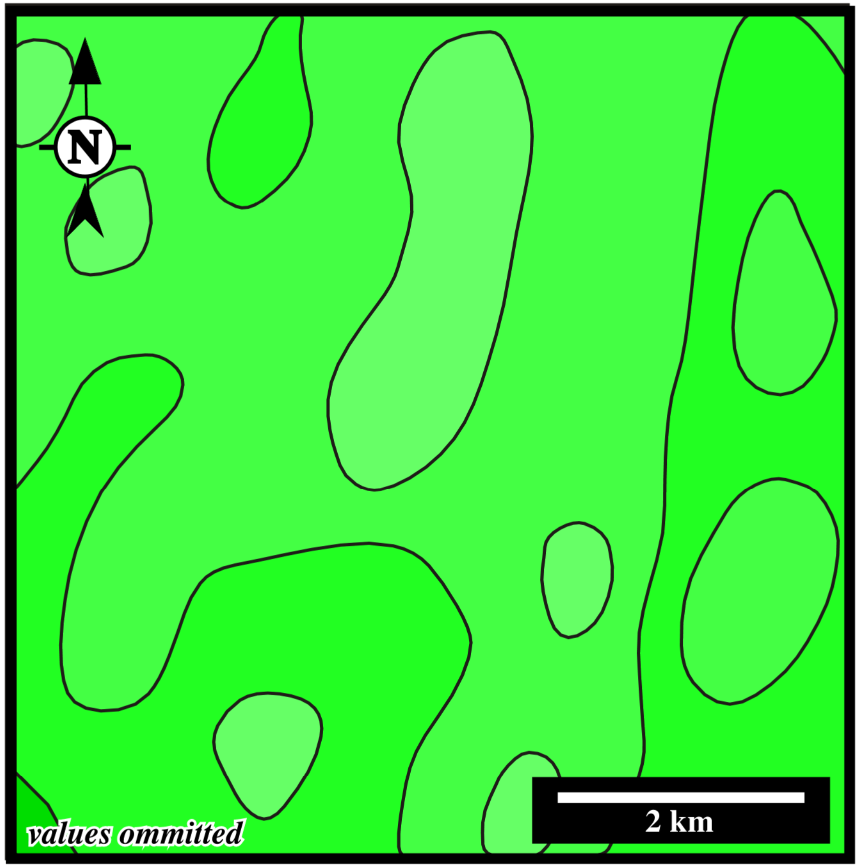


Fig. 20- Here above is illustrated the second vertical derivative map of Bouguer anomaly of the area covered by fig. 18. The enhancement induced by the derivative allows a better localization of the sources.

SVD of Residual

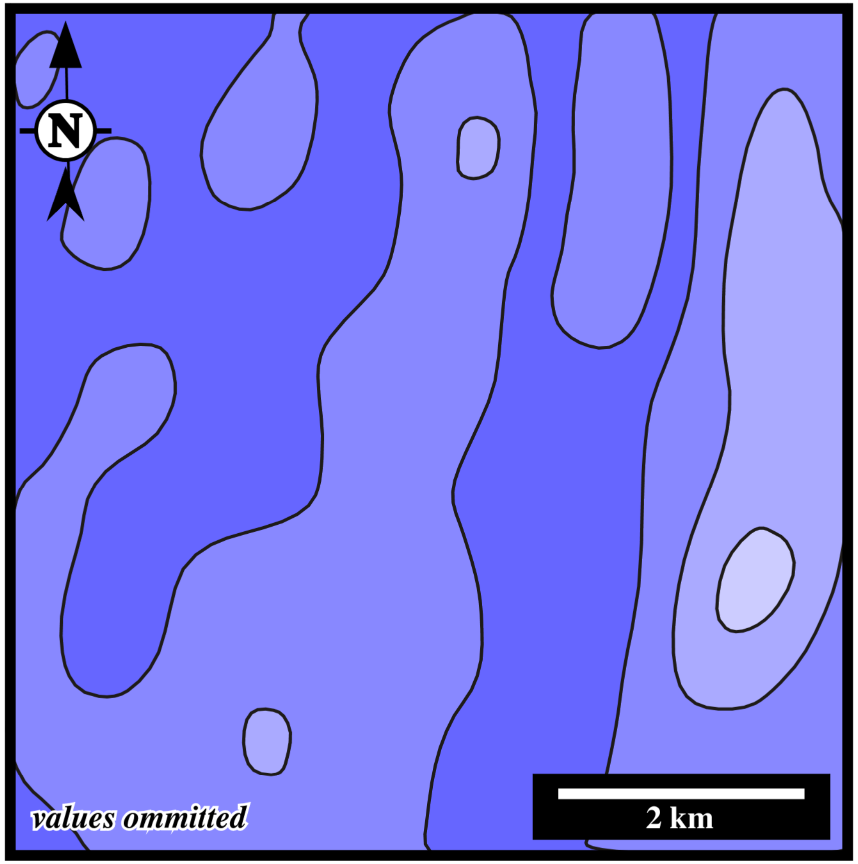


Fig. 21- As for the Bouguer anomaly, the residual can be enhanced by the second derivative. Indeed, as illustrated above, the location of the gravimetric sources is more evident than in the residual map (fig. 19). On this subject, the comparison of fig. 21 and fig. 19 is more than evident.

Geologic Interpretation

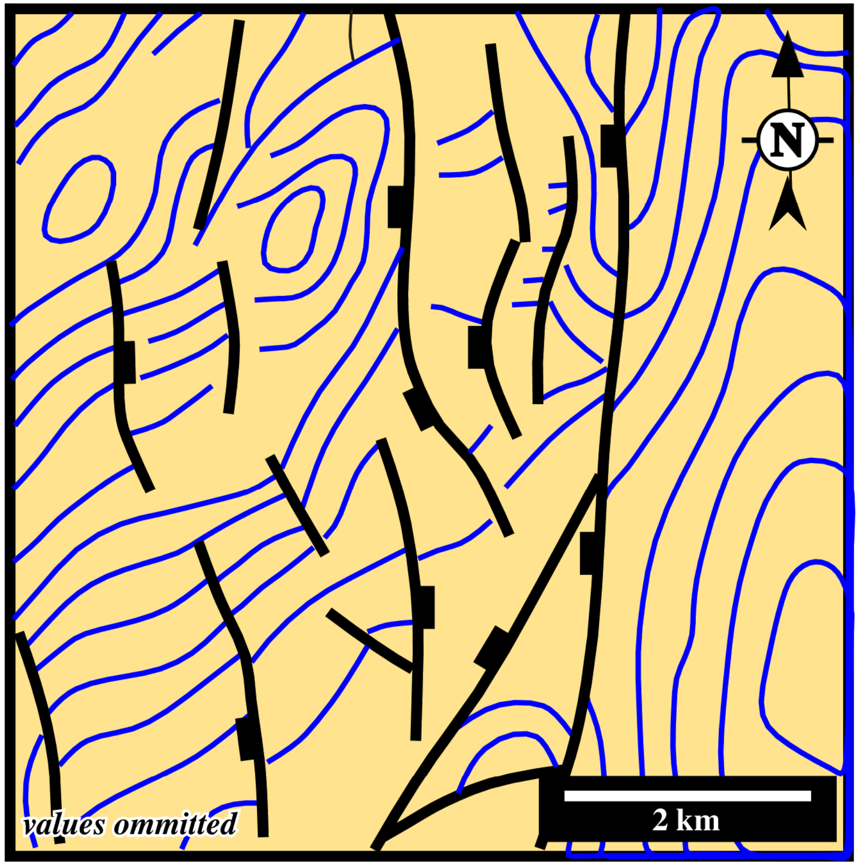


Fig. 22- An extensional geological monocline, as illustrated above, fits with the gravimetric data (figs. 17 to 21). The area seems to be affected by an extensional tectonic regime characterized by a σ_1 (maximum effective stress) vertical and σ_2 and σ_3 horizontal, with σ_2 striking roughly north-south. The eastern area seems match with a buried hill of the basement. Geologic interpretation must be completed and tested by field, subsurface and seismic data.

g) Geological Models

1- Anticline Model (fig. 23)

During a compressive tectonic regime (σ_1 horizontal) with a $\sigma_3$vertical, the sediments are shortened and uplifted by folding and thrusting. The folds are concentric anticlines and synclines, that is to say, when pictured in a stereographic projection they lie on a great circle. In an anticline, as shown on fig. 23, there is a lateral change of the density of the sediments. The denser sediments (shallower burial) form the heart of anticline. Hence, an anticline model (fig. 23) with $\delta\rho$ = 0.17 g/cm^3 gives a typical antiform gravimetric anomaly (bottom of fig. 23).

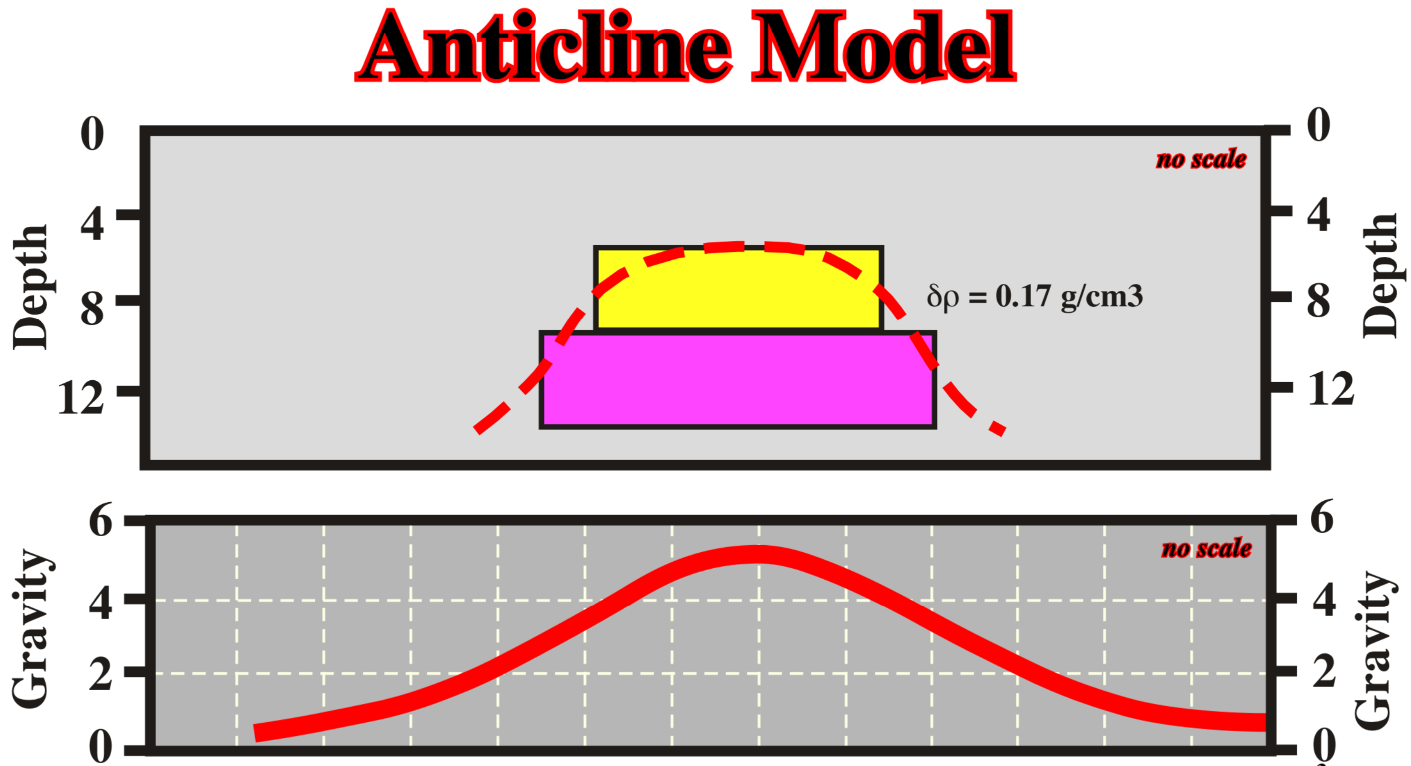


Fig. 23- Geological model of an anticline structure and its gravity response with for a $\delta\rho$ = 0.17 g/cm^3 are depicted above. $\delta\rho$ represents the density difference between the heart of the anticline and the surrounding sediments. Such a difference is a consequence of sedimentary burial.

2- Thrusting Model (fig. 24)

In a thrust or reverse fault, the sediments of the upthrown block (hangingwall) are shortened and uplifted, whereas those of the downthrown block (footwall) are relatively undeformed. In such conditions, as illustrated on fig. 24, the hangingwall sediments are denser than those of the downthrown block. In addition, as the hangingwall sediments are shortened, by folding, the structures' heart is denser. The gravimetry response of such a geological structure is shown on fig. 24, where a strong positive anomaly correlates with the upthrown block.

Reverse Faulting

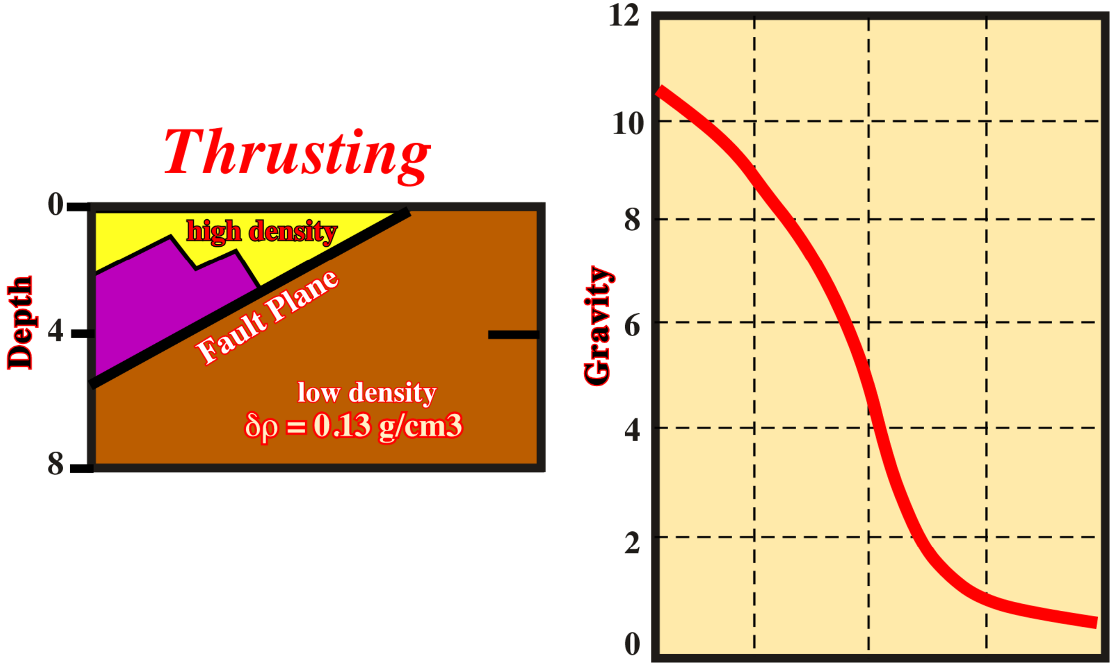


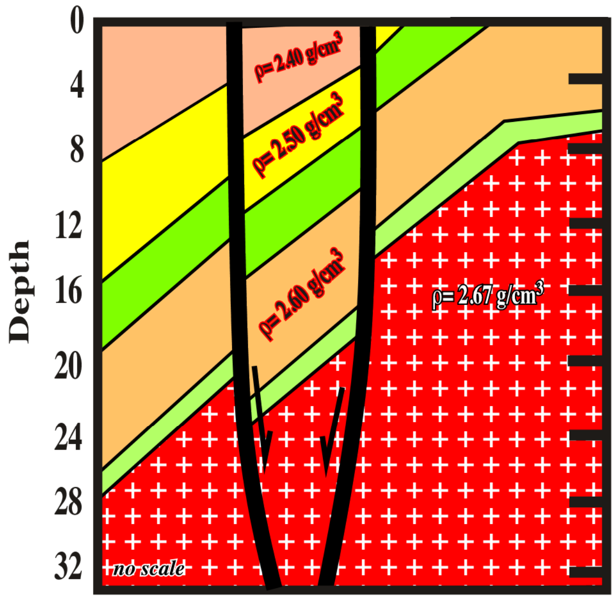
Fig. 24- Geological model and gravity response for a thrust fault (or reverse fault), in which the density difference between the hangingwall and the footwall, $\delta\rho$ = 0.13 g/cm^3.

3- Normal Faulting (fig. 25)

During an extensional tectonic regime (σ_1 vertical), the sediments are lengthened: (i) lengthening is made by normal faults, (ii) normal faults strike parallel to σ_2, i.e. the intermediate effective stress, (iii) hangingwall sediments are buried deeper than those of the upthrown block, hence density will be higher due to a stronger compaction. In a pre-compaction normal faulting:

(i) Density and velocity of sediments of the downthrown blocks are higher than those of the upthrown blocks,
(ii) When the amplitude of the vertical throw is big enough, the associated lateral changes in density and velocity will create relatively important gravimetric anomalies.

Normal Faulting



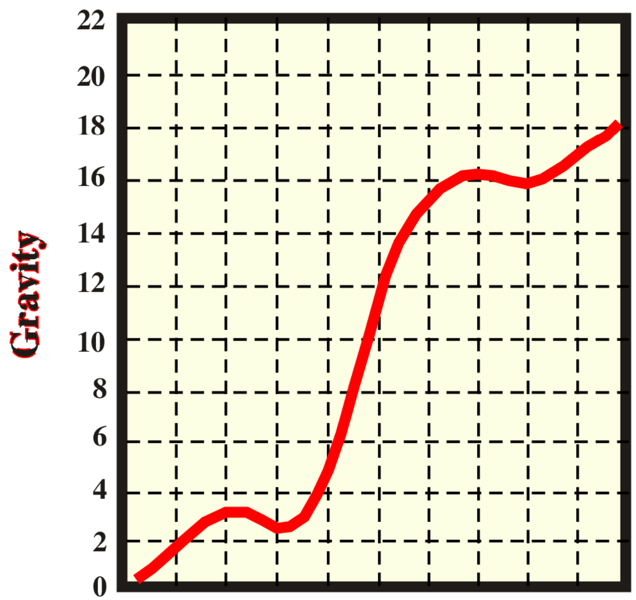


Fig. 25- In normal faulting, the hangingwall sediments are denser that the sediments of the upthrown block. Hence, as illustrated in the gravimetry profile, the associated gravimetric anomaly can be relatively sharp.

4- High Density Beds (fig. 1.26)

In a geological model with high-density beds, the dips of the sedimentary beds can range from 10° to 60°.

- Assuming that sedimentary tilting is **pre-compaction**.
- There are lateral changes in density and velocity.

Higher are the dips of the beds, the bigger are the lateral changes in density and velocity

- Lateral contrasts are big enough to create sharp gravity anomalies, as illustrated below.

High Density Beds

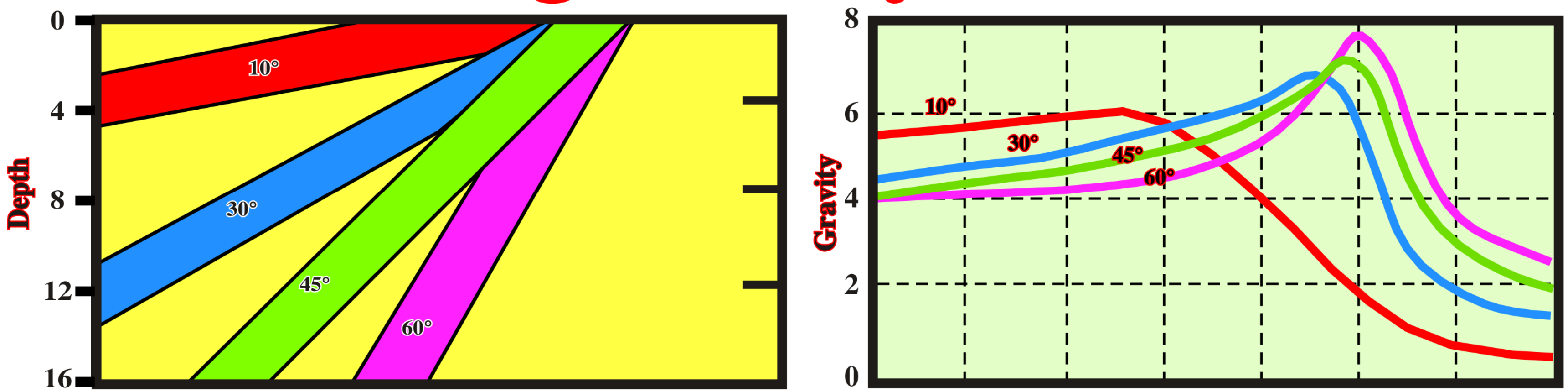


Fig. 26- On this geological model, the dips of the strata increase in depth. Hence, due to compaction, one can say that average density and acoustical impedance increase too. So, gravity anomalies can be associated with such a tectonic behaviour.

In conclusion:

- **Gravity maps** are seldom used for detailed interpretation.
- **Seismic surveys** are generally more useful for detailed studies in small areas.
- Like magnetic, **gravity maps** are useful to show the broad architecture of sedimentary basins.
- In gravimetry, **low-density depocenters** appear as negative anomalies (salt domes, rim synclines).
- **Buried hills** of dense basement rock, in gravimetry, show up as positive anomalies.

C) Seismic Exploration Basic Review

Basics Review

Seismic exploration is supported by the **elastic wave propagation theory**. The main relevant basic principles are:

a) Conservation of energy.

b) Equations of motion (Newton's laws).

c) Reciprocity.

d) Linearity.

Solutions of acoustical problems are quite simple in homogeneous and isotropic environments (fig. 27). However, such approximation most geological cases, is rough.

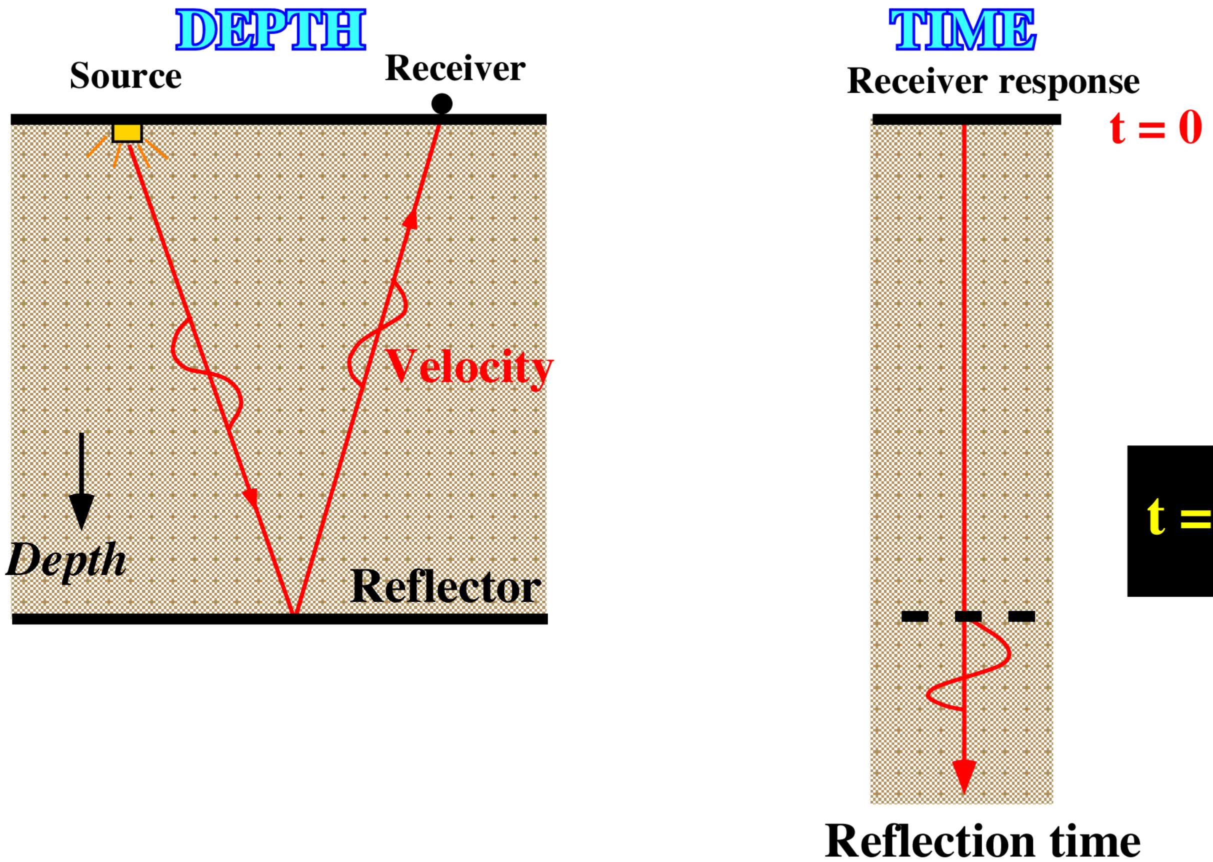
Theoretically, we can solve wave propagation equations and predict, if we know the movement of a particle at a point, the resultant movement at any other point. This is particularly true as long as we know **the physical characteristics of the environment**, especially the longitudinal velocity.

Seismic data acquisition (fig. 28) is desined to efficiently record, through **surface receivers**, energy from shot point after it is reflected off of subsurface discontinuities.

Conservation of energy (basic principle) implies that input energy must be either **transmitted** (surface wave, first arrivals) or **reflected**, or **refracted**, or **scattered** (diffractions), or **converted** into another wave type, or **absorbed** into heat. Conventionally, output energy is split in useful reflected energy or other forms of energy respectively called:

Signal and Noise

Seismic Reflection Principles



$$t = \frac{2 \times \text{depth}}{\text{velocity}}$$

Fig. 27- These sketches illustrate, in depth and time, the basic seismic mechanisms. The source, the depth of the reflector, the velocity of the sediments above the reflector, and the receiver are the main components of the seismic surveying. The time response is given by the depth of the reflector multiplied by the velocity of waves within the sediments overlying the reflector.

Seismic Data Collection

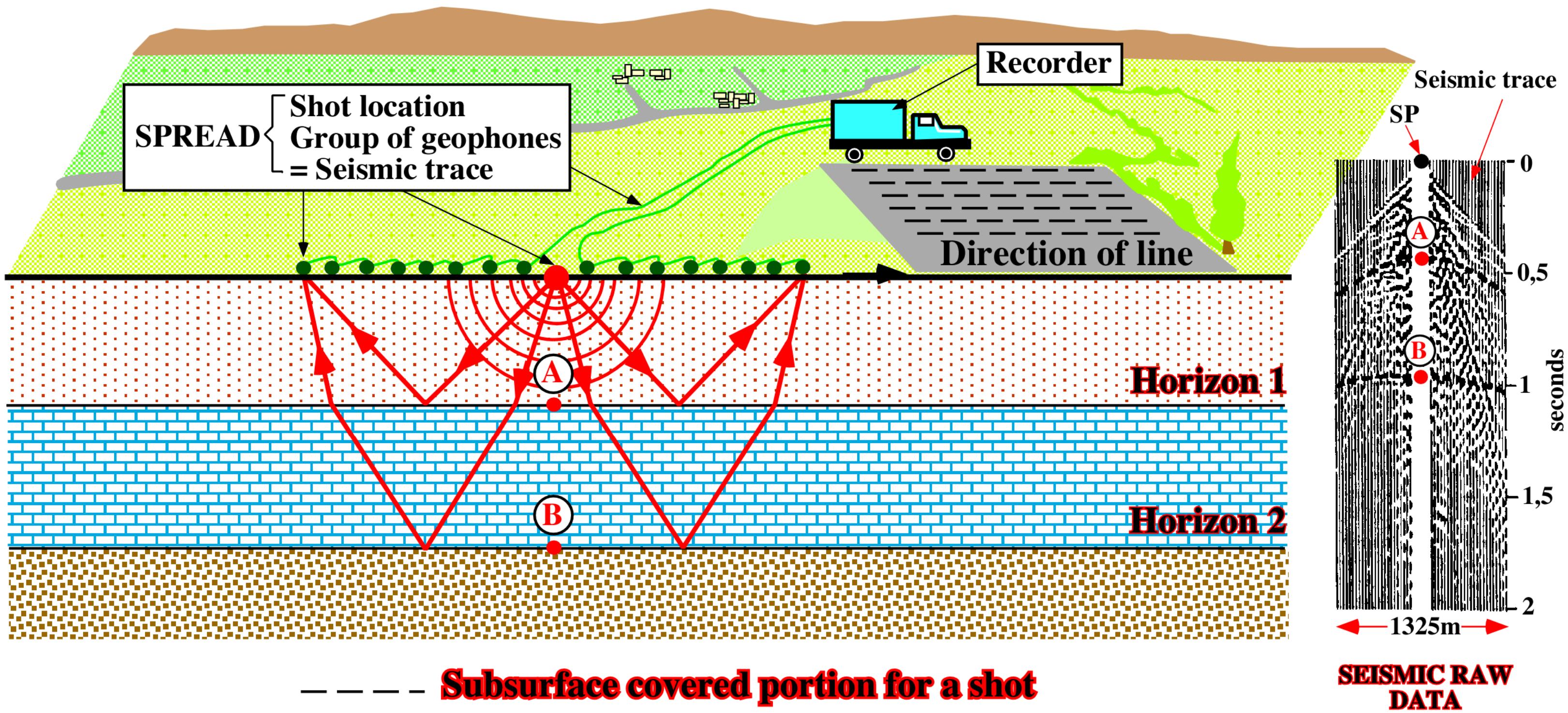


Fig. 28- Acquisition and processing of seismic data require several steps. This cartoon illustrates land acquisition opf seismic data. The source generates a low-frequency signal, which is reflected off an underground layer. A series of geophones picks up the arrivals of waves reflected at different angles to the source. The source and geophones are then moved, enabling every geophone to pick up reflections from various angles. These reflections are recorded on tape and the recordings displayed. Computer editing removes any noisy traces, and reflection signals from a common depth point are collected.

Seismic Methods

Incident energy on an interface should be either:

- **Reflected**, that is to say, the energy does not cross the interface (fig. 29),
- **Refracted**, i.e. the energy travels along the interface, or
- **Transmitted**, when the energy crosses the interface.

Snell's law controls all reflections within the critical angle, after which refraction occurs (fig. 30). The reflection is a function of the **reflection coefficient.** It corresponds to the ratio of the amplitude of the reflected wave to the incident wave (reflectivity). The ratio of the reflected energy to the incident energy is the **reflection coefficient square**.

Depending on what we are looking for, we will have to select where to put receivers to pick either reflections or refractions* for a given shot-point location and target.

D) Seismic Reflection Basics

The basic principles of seismic reflection can be summarized in three steps:

(i) When a seismic wave is generated, the geophone picks up **the wave's two way travel time** down to a reflecting layer and back.

(ii) **Moving the shot point and geophone** generates a series of reflections of the layer.

(iii) Reflections show up as **wiggly trace** on the seismic record, which can be correlated across the profile.

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*Refraction method was extensively used before the sixties. Unfortunately, today it is mainly limited to weathered zone bottom determination (small refraction).

Reflection, Refraction
First Arrival

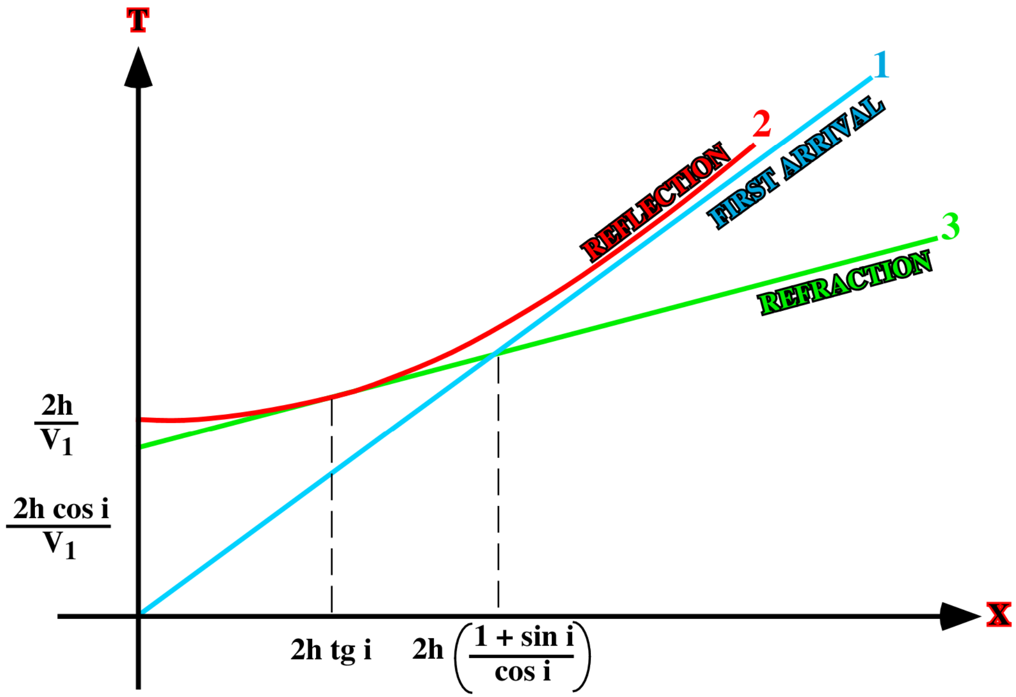

Fig. 29- This figure illustrates the travel-time curves for direct (first arrival), reflected and refracted rays in the case of a simple two-layer model. The first arrival of seismic energy at a surface detector offset from a surface is always a direct ray or a refracted ray. The direct ray is overtaken by a refracted ray at the cross-distance 2h {(1+sin i)/cos i)}. Beyond this offset distance, the first arrival is always a refracted ray. Since critically refracted rays travel down to the interface at the critical angle there is a certain distance, know as the critical distance (2h tgi), within which refracted energy will not be returned to surface. At the critical distance, the travel times of reflected rays and refracted rays coincide because they follow effectively the same path. Reflected rays are never first arrivals. They are always preceded by direct rays and, beyond the critical distance, by refracted rays also.

Acoustic Impedance
Reflection Coefficient

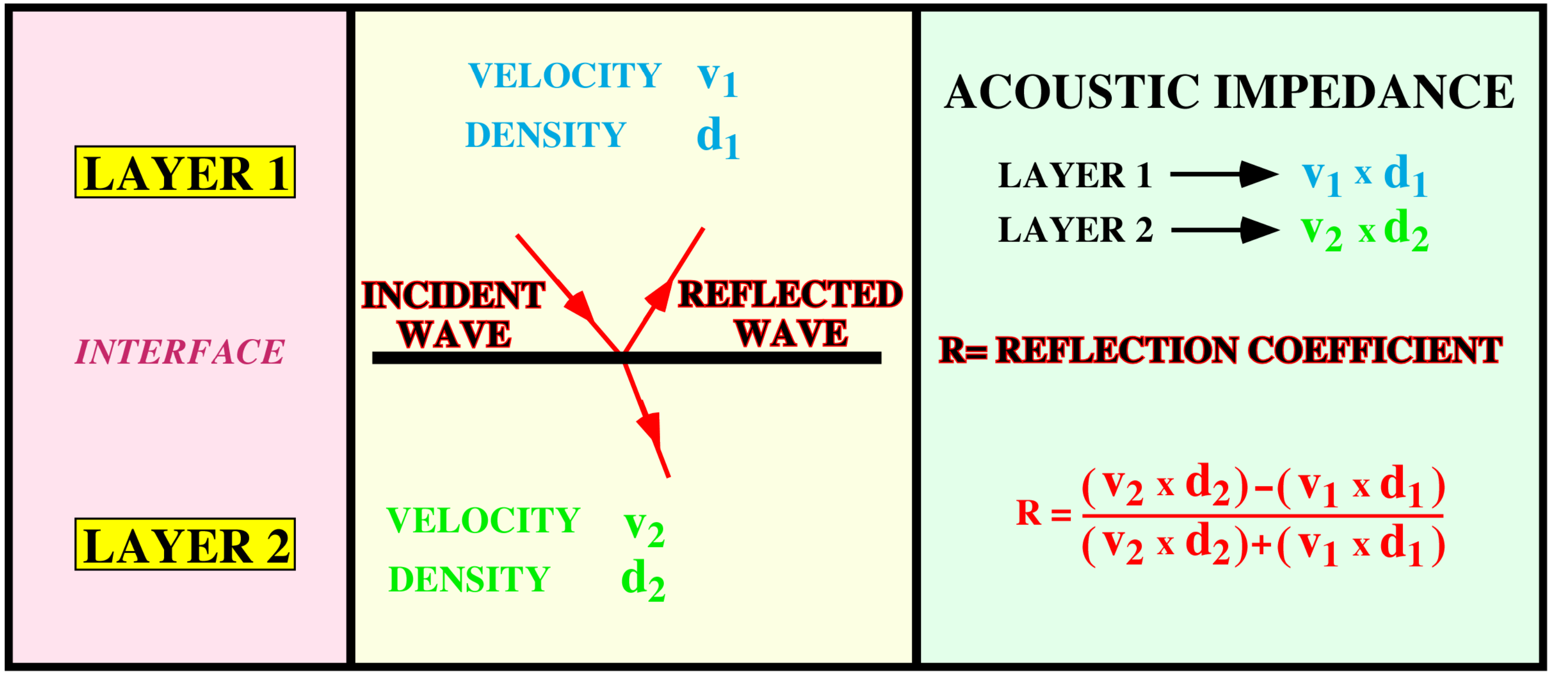

Fig. 30- Assuming two sedimentary layers with different velocities (v_1, v_2) and different densities (d_1, d_2), i.e. with different acoustic impedances (v d), the reflection coefficient is the ratio between the difference of the acoustic impedance and the addition of the acoustic impedances. Notice that oblique incident waves on the interface are broken into reflected and refracted waves.

On these notes, I assume that all explorationists are more or less familiar with the essentials of seismic prospecting, that is to say:

- Field work.

Spread, Source, Array, Digital Recording, etc.

- **Processing.**

Gain recovery, Filtering, Deconvolution, Velocity analysis, Stacking, Migration, etc.

- Signal Theory.

In waveforms of geophysical interest, the **signal** is almost invariably superimposed on unwanted **noise**. In favourable circumstances, **the signal / noise ratio (SNR) is high**, so the signal is readily identified and extracted for subsequent analysis. However, very often, the SNR is low and **special processing** is necessary to enhance the information content of waveforms. In order to make it clear, the aim of the geophysicist is:

- At acquisition stage:
To find the best compromise for **penetration** and **resolution** of the data according to the exploration target.

- At processing stage:
To extract the maximum benefit of recorded data in terms of **reliability**, **geometrical control**, and **definition**.

- At interpretation stage:
To organize observations through an understanding and acceptable *a priori* geological model. In other words, interpreters start always with a geological problem. In order to solve it, they propose a hypothesis, which they try to falsify. If the refutation test is positive, they get a new problem, which obliges them to propose a new hypothesis ...., a new test ..... and so on. This scientific method is often called pragmatic, rational or hypothetico-deductive.

Seismic Reflections

The sound waves travel in all directions, but only those travelling almost directly downward can be reflected off structures (interfaces) underneath the explosion. A seismic reflection (fig. 31) is produced at any break of **acoustic impedance** (product of the seismic velocity and bulk density).

Positive & Negative Reflections

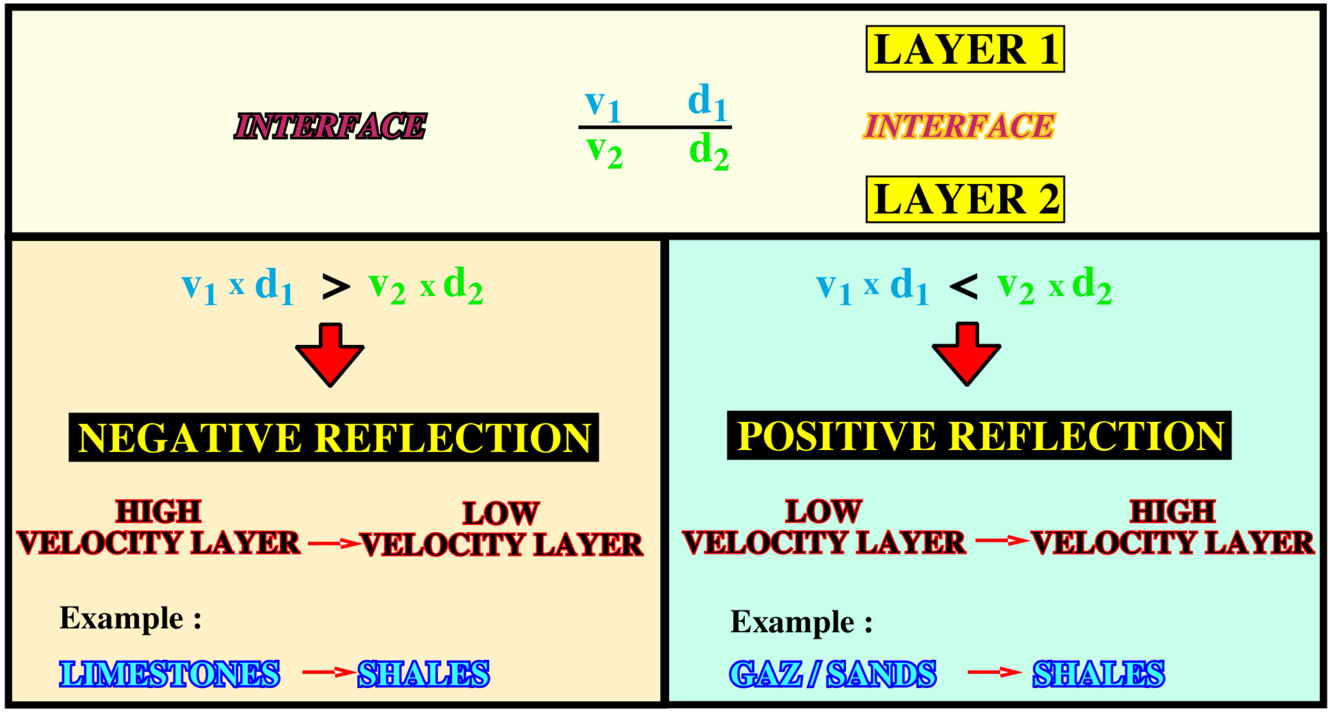

Fig. 31- A negative reflection occurs when the acoustic impedance of the upper layer of the interface is higher than that of the lower layer (ex: limestone / shale, or shale /sandstone). When the acoustical impedance of the lower layer is higher than that of upper layer the associated reflection is positive (ex: shale /limestone, etc.).

Seismic reflections can be positive or negative and their **polarity** can be to the right or to the left (figs. 32 and 33). Seismic waves are modified by acoustic impedance breaks and by changes of amplitude and polarity.

Polarity Conventions

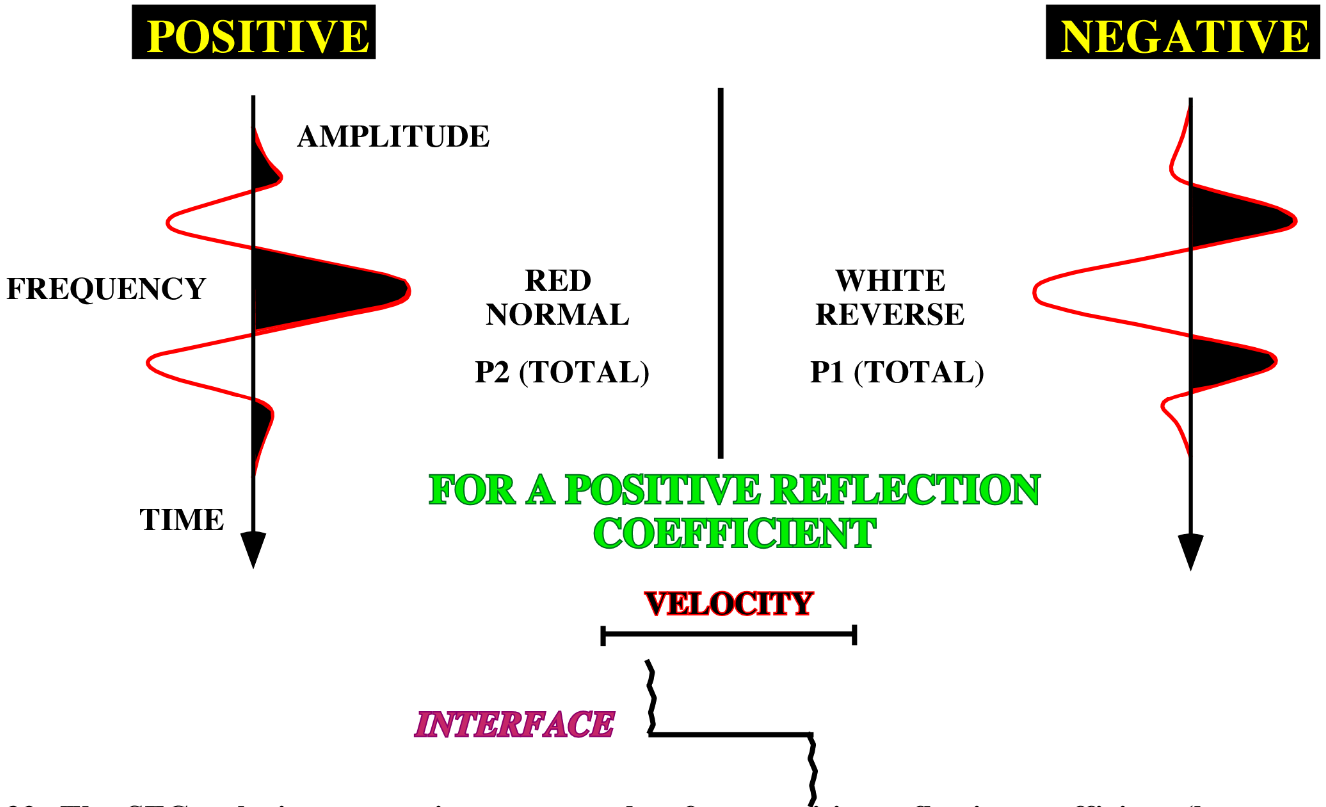

Fig. 32- The SEG polarity convention assumes that for a positive reflection coefficient (low acoustical impedance / high acoustical impedance) the amplitude is expressed by a deflection to the right of the base line (black) and to the left (white) for a negative polarity.

In general terms the **amplitude** for a symmetrical waveform is half the orthogonal distance between the crest, or ripple, above the adjacent troughs (for asymmetrical and non-periodic systems, others definition have been proposed).

As they arrive at the Earth's surface, the amplitude of a seismic signal decreases rapidilly with time. This amplitude range is very large, often a million to one or more:

- The eye can appreciate this range, from 1mm to 1 km, but it is clearly quite impractical to present the results in this range.

- On standard cross-sections the eye does not appreciate anything much outside a 10 to 1 range in amplitude, that is to say from 0.1 mm to 1mm.

- Amplitudes must be constrained within this range, either by automatic (data dependent) processes or purely functional changes.

Data Acquisition

1- Onshore

On land the returning sound wave is detected by a listening device called a **geophone**. A single shot recorded by a single geophone is recorded on a strip chart as a long line, with a pulse representing the time when the reflected sound wave returned. If more than one reflecting surface is encountered, there will be more than one pulse on the trace. The vertical scale on most seismic lines is therefore **two-way travel time (t.w.t.)** in seconds.

Knowledge of the **average seismic velocity** of various rock types enables interpreters to calculate the actual depth of reflecting layer in metres rather than in seconds, but this is needed only when they are trying to match seismic records with well logs or surface outcrop. A single strip chart is as one-dimensional as a borehole record. To get two-dimensional layers and other structures, an array of recording points is needed.

Every point records the shot separately and produces a strip chart. When all the charts are lined up, the pulses, or reflections from the same layer also line up from one chart to the next, and the first approximated measurement of the layer is made. This is called **picking** the marker reflections.

Reflection Seismogram

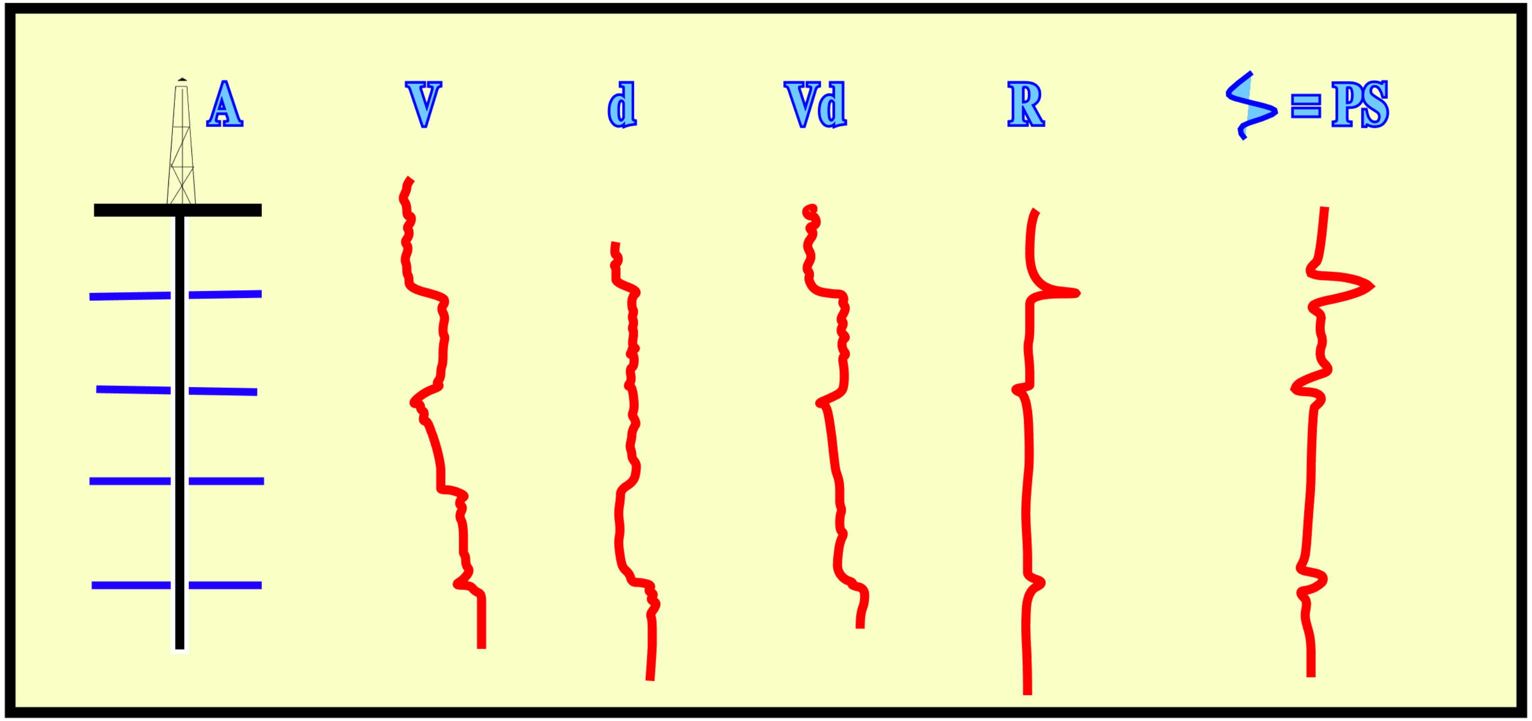

Fig. 33- The reflection seismogram can be seen as the convoluted output of a reflective function with an input pulse. Assuming the pulse shape remains unchanged as it propagates through such a layered ground, the resultant seismic trace may be regarded as the convolution of the input pulse with a time series known as a reflectivity function (R). The amplitude of each spike is related to the reflection coefficient of a boundary and a travel time equivalent to the two-way reflection time for that boundary. This time series represents the impulse response of the layered ground. V represents the velocity of the seismic waves in the sedimentary intervals drilled by the well A, d represents the density of the sedimentary intervals, Vd is the impedance profile and R is the reflectivity function. PS is the pulse shape.

The geophones in an array are laid out in a traverse at regular intervals away from each record truck, which contains the electronics to record the signals and the computer to process and interpret them. The sound is then generated. Every geophone in the line array picks up the direct reflection at a time that depends on its distance from the acoustic source.

- The earth motion, which the geophysicist sets out to record, consists of the wanted and unwanted parts of the earth response to the input.

- Earth is a noisy place.

- There are many other seismic and acoustic sources in operation at any time.

- The sources that are very close to the detectors produce signals, which appear quite random.

  Ex: Grasshoppers on the geophones.

- Arrival from more distant sources may be recognizable on many detectors.

- Distant sources generating periodic waveforms, such as ships, trains, airplanes, power stations and other industrial processes, will add rather similar wave-forms to all the data.

- The skills of seismic data gathering are directed to **reducing the noise content in the recorded signal**, and data processing to **improving still further the signal-to-noise ratio**.

To improve the signal-to-noise ratio after a shot is made, the source and its array are moved a distance down-line, so that the reflections from the same layer will be picked up by geophones from slightly different positions. This is called the **common-depth-point** method.

By repeating the slots and measuring from slightly different positions along a linear transect, the signals are recorded many times and can be stacked. This amplifies the signals and screens out the noise because the noise has no regular pattern along the line. Finally, all the signals from the single traverse are collected, screened by the computer, and printed out as a seismic profile.

On Land 3D Collected Data

Crosses Array Method

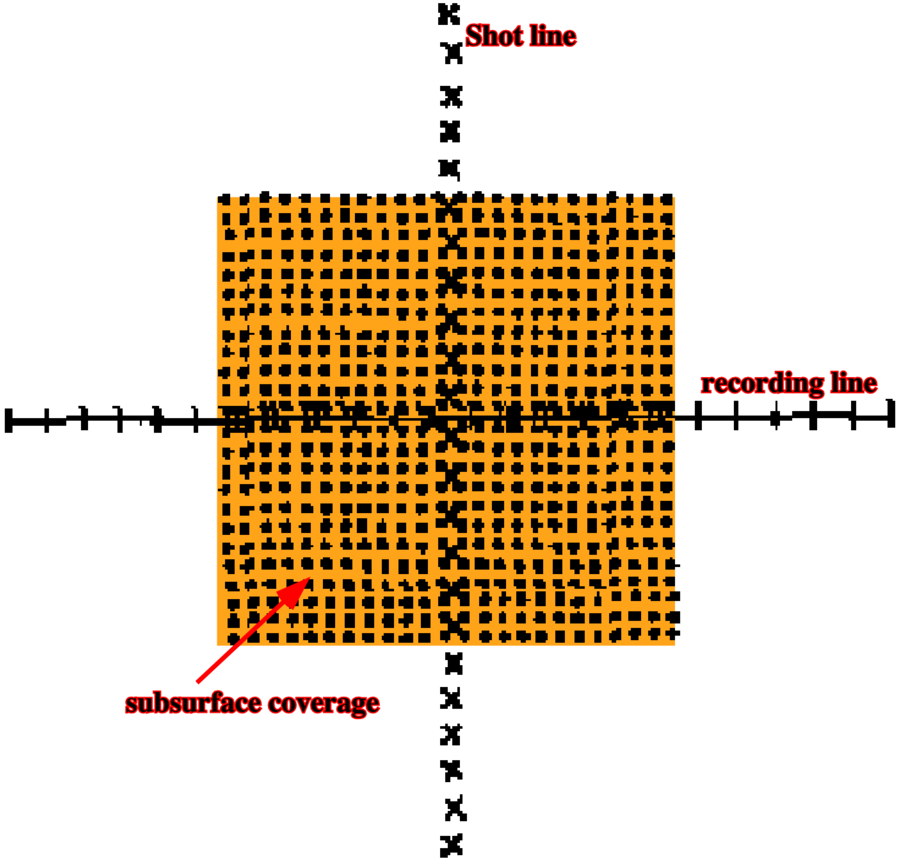

Fig. 34- On land, three dimensional data are normally collected using the cross array method, in which shots and detectors are distributed along orthogonal sets of lines (in-lines and cross-lines) to establish a grid of recording points. This sketch illustrates for a single pair of lines, the area coverage of a subsurface reflector.

It should be noticed that if most of seismic reflections are associated with chronostratigraphic horizons or stratification planes, it is possible that significant geological interfaces are notcaptured as seismic reflectors. That happens when there is no impedance break associated with the interface:

$$V_1 \text{ x } d_1 = V_2 \text{ x } d_2$$

2- On Offshore

The basic method of acquiring seismic data offshore is much the same as that of onshore, but it is simpler, faster and hence cheaper. A seismic boat replaces a truck as the controller and recorder of the survey. This boat trails an energy source and a cable of **hydrophones**, again termed a **streamer** (fig. 35). It is possible for one boat to operate several energy sources, but experience has shown that more bangs is not necessarily best.

- Streamer lengths can extend for up to 6000 m to the annoyance of fisher folks.
- Currently, surveys vessels can operate up to three energy sources whose signals are received by hydrophones on 8 to12 streamers, up to 3000 m in length, with a total survey width of 800 m.

In marine surveys, dynamite is seldom used as an energy source:

- For shallow high-resolution surveys, including sparker and transducer surveys, **high frequency waves** are used.
- For deep exploration, the **air gun** is widely used as the energy source.

In this method, a bubble of compressed air is discharged into the sea. Usually a number of energy pulses are triggered simultaneously from air guns:

- The air guns emit energy sufficient to generate signals between 5 and 6 seconds two-way-time.
- Depending on interval velocities, these signals may penetrate to more than 5 km.

The reflected signals are recorded by hydrophones on a cable towed behind the ship. The cable runs several meters below sea level and may be up to 6 km in length. As with land surveys the CDP method is employed and many recorders may be used.

Offshore Acquisition

Seismic Data

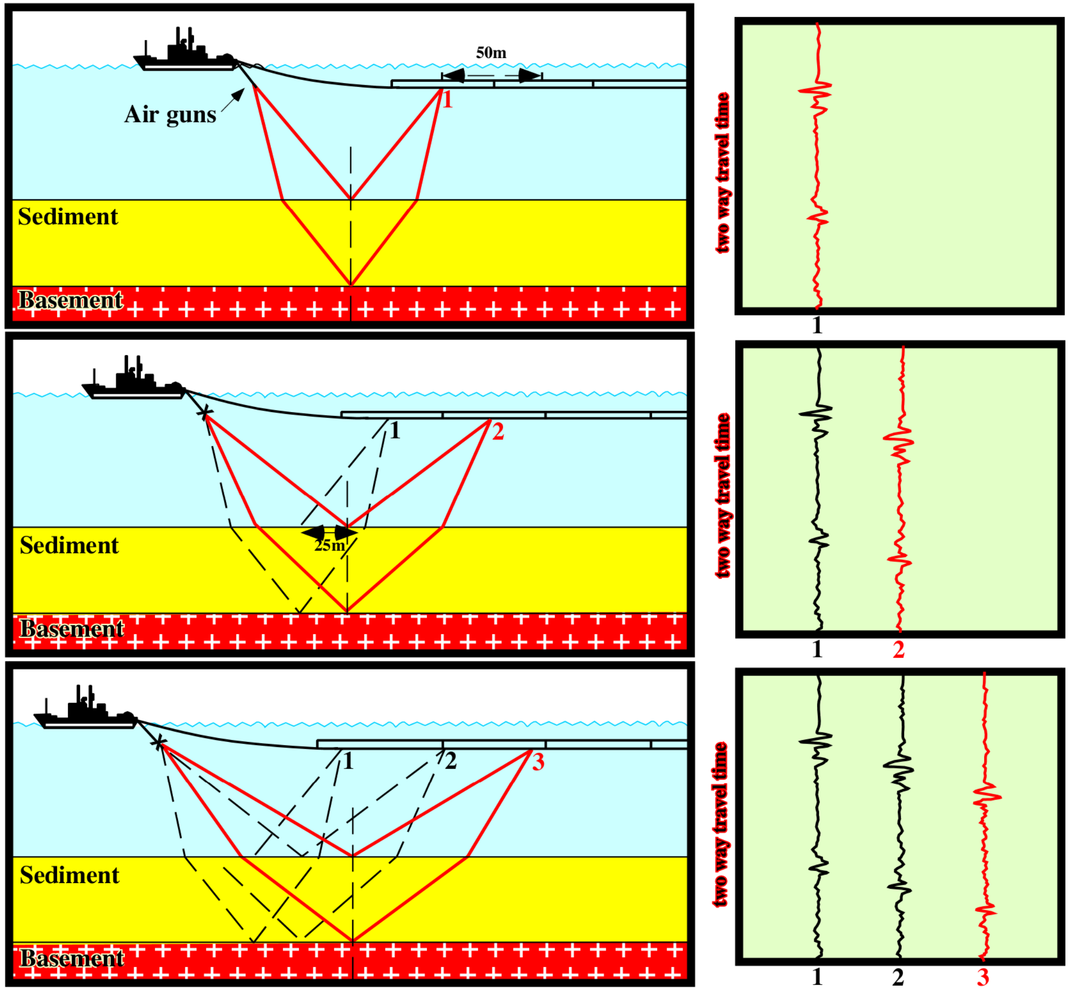

Fig. 35- Example of offshore seismic data collection (three traces).

The reflected signals are transmitted electronically from groups of hydrophones along the cable to the recording unit on the survey ship. Other vital equipment on the ship includes a **fathometer** and **position fixing devices**:

- The accurate location of the shot points at sea is obviously far more difficult that it is on land.

- Formerly, this was done either by **radio positioning**, or by getting fixes on two or more navigation beacon transmitters from the shore.

- Nowadays, **satellite navigation systems** enable pinpoint accuracy to be achieved.

Signal Correction

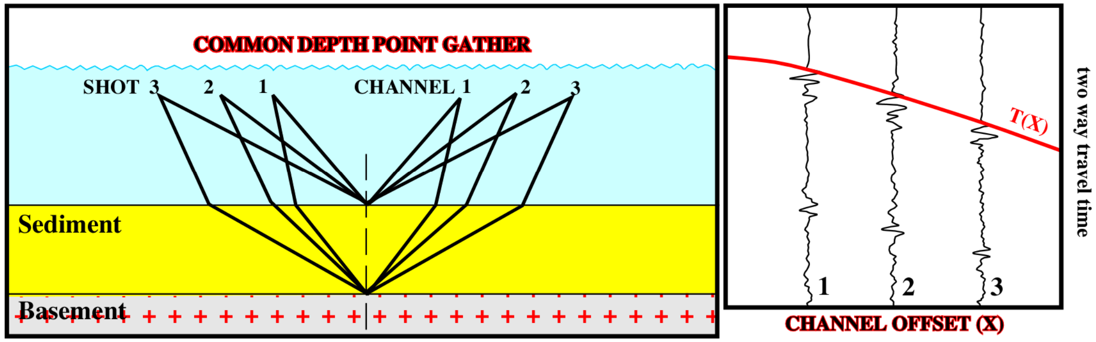

Fig. 36- The signal correction attempts to eliminate the time differences between reflection times, resulting from changes in the outgoing signal from shot to shot.

The steps in signal reprocessing are:

- Gathering
- Offset
- Enhancement
- Stack
- Addition

C.Cramez
Switzerland

Stacking of Seismic Data

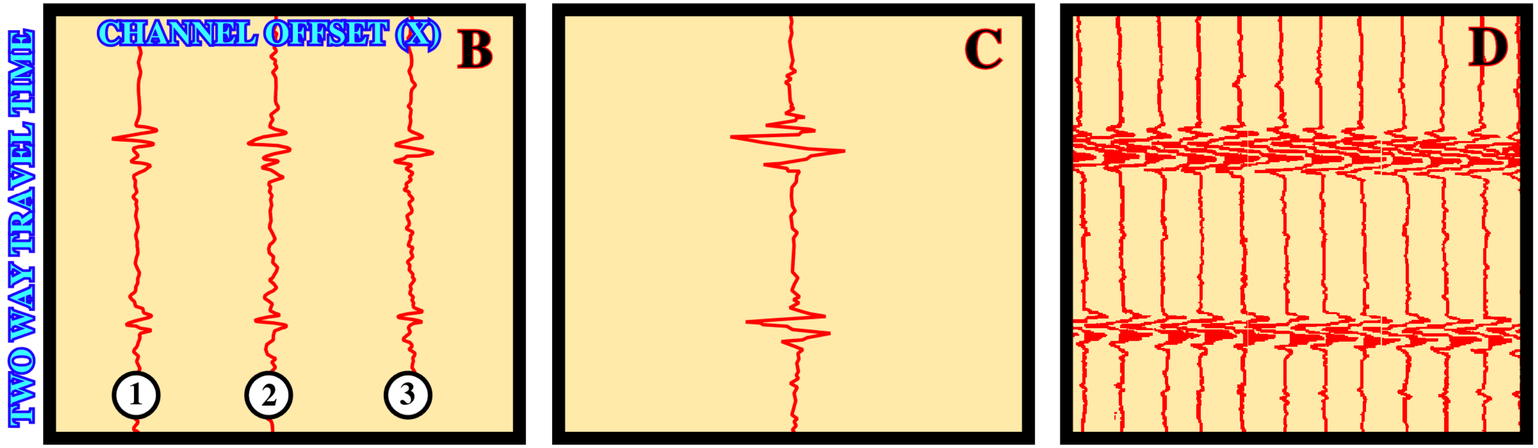

Fig. 37- Since the recording reflections are gathered from a CDP, the traces are shifted so that corresponding peaks have the same arrival time. Then, the traces are added and the reflection peaks are enhanced. Finally, thousands of point profiles are put side by side and the peaks area darkened according to the SEG convention.

At sea, three-dimensional data may be collected along closely-spaced parallel tracks with the hydrophone streamer feathered to tow obliquely to the ship‘s track such that it sweeps across a swathe of the sea floor as the vessel proceeds along its track. By ensuring that the swathes associated with adjacent tracks overlap, data may be assembled to provide the coverage of subsurface reflectors.

In the alternative dual source array method, sources are deployed on side gantries to port and starboard of hydrophone streamer and fired alternatively (fig. 38). Dual streamers may similarly be deployed to obtain three-dimensional data.

High quality position fixing is a prerequisite of three-dimensional marine surveys to ensure that the locations of all shot-detector midpoints are accurately determined.

Offshore Collecting 3D Data

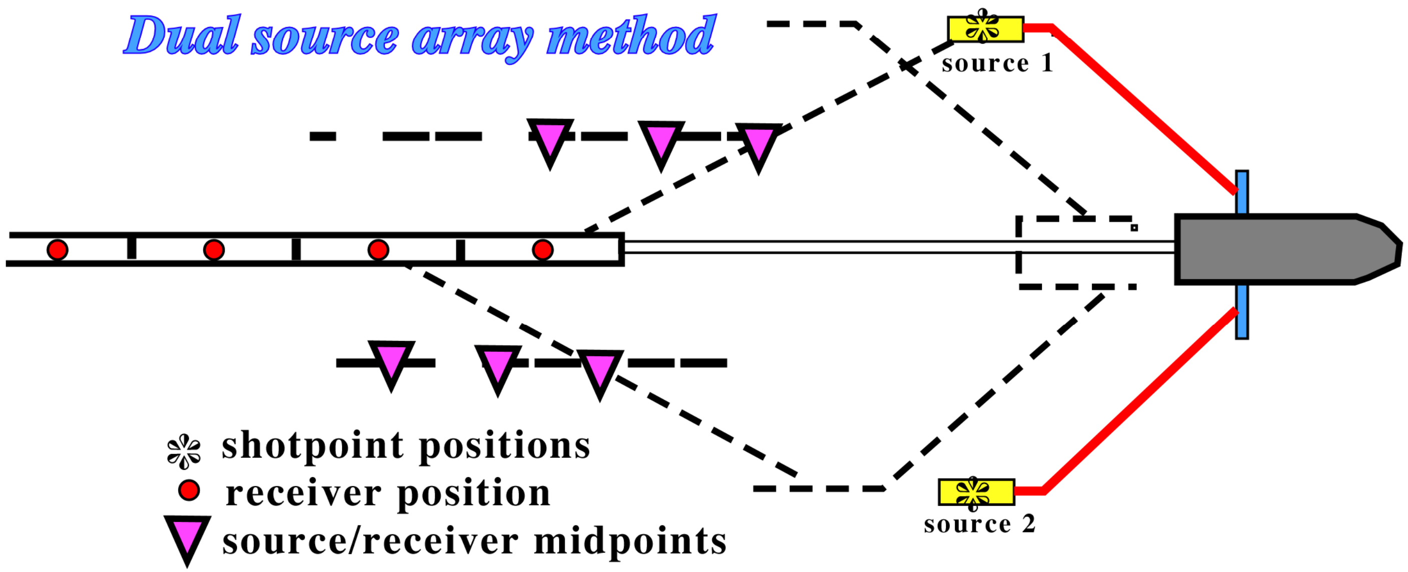

Fig. 38- This cartoon illustrates the dual source array method of collecting three-dimensional seismic data at sea. Alternative firing of sources 1 and 2 into the hydrophones produces two parallel sets of source detector midpoints.

Position fixing is normally achieved in near shore areas using radio navigation systems, in which a location is determined by calculation of range from onshore radio transmitters. Beyond the range of such systems satellites navigation is used, with **Doppler sonar** being employed to determine the velocity of the vessel along the survey track for interpolation of position during the time interval between individual satellites fixes.

Simplified Seismic Processing

(Klemperer and Peddy, 1992)

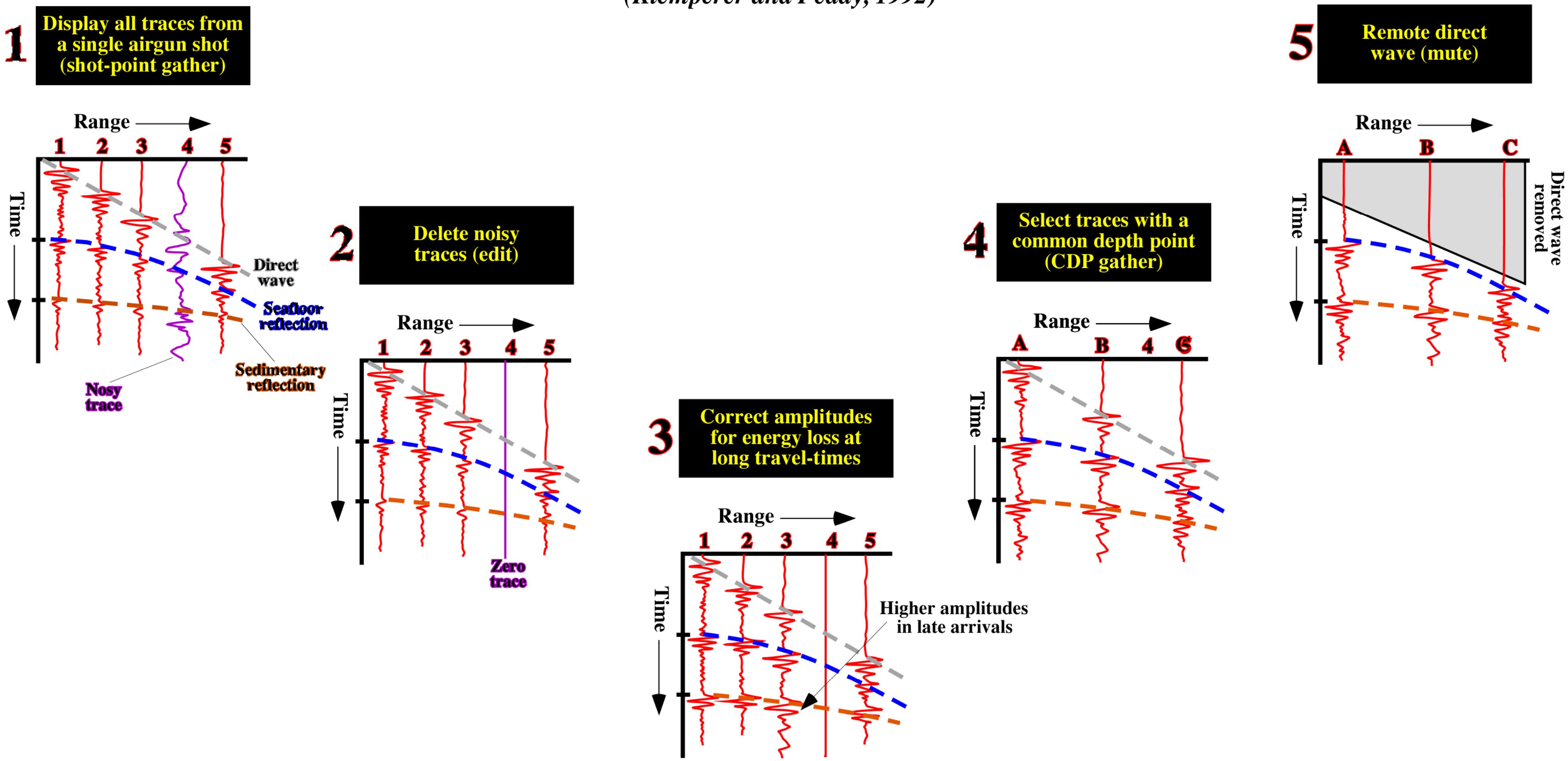

Fig. 39- The traces illustrated in part (1) result from a single shot, and were recorded by a single receiver. The direct wave (refracted wave) appears at a time proportional to the receiver distance from the shot, while the reflections lie on a hyperbolic travel-time curve. Any bad or noisy traces are deleted (2). The seismic amplitudes recorded decrease with increasing travel-time because the reflectors are further away, so the weaker amplitudes are boosted (3). Then the traces are resorted so that all traces with an identical source-receiver midpoint are gathered together in (4), one trace each from (1), (2), and (3). The direct wave is removed (the shaded area in 5). (see next)

Simplified Seismic Processing

(Klemperer and Peddy, 1992)

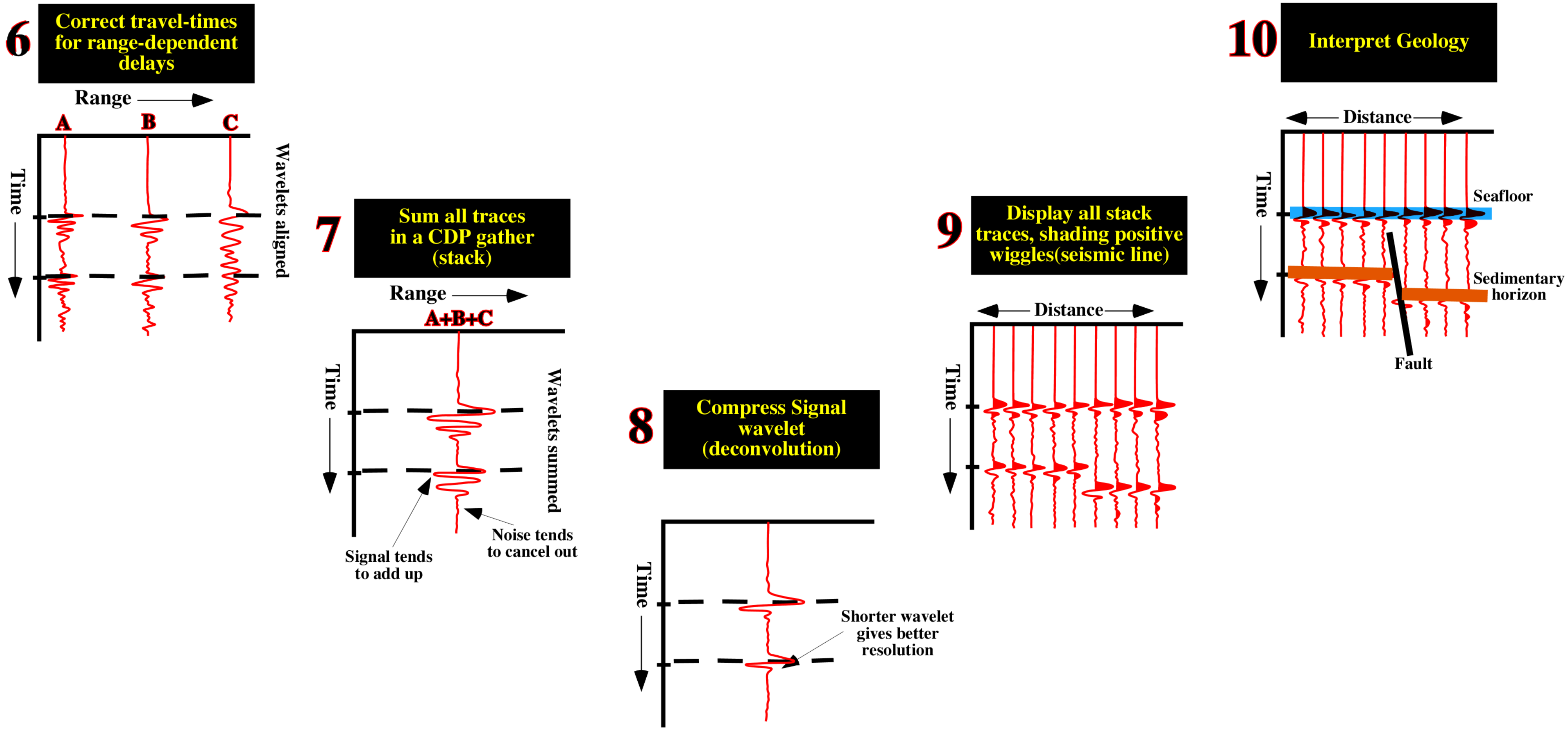

Fig. 40- Each trace is separately corrected for the time-delay appropriate for its source-receiver offset (6). This is known as the normal move-out, or NMO correction. The wavelets from each reflection are now lined up, as if each trace had been recorded with coincident source and receiver (i.e., without source-receiver offset delays), and all the traces in the gather can be summed (stacked) to give a single trace in (7) with a higher signal-to-noise ratio. If the wavelet is rather reverbatory, or lengthy, then its resolution is poor, but can be shortened by a digital filtering technique called deconvolution (8). Finally, all the traces are displayed as a seismic section and may then be interpreted (Selley, 1998).

Seismic Sections

Since CDP profiling data from two-dimensional surveys are conventionally displayed as a **seismic section,** in which the individual stacked seismograms are plotted side by side, in close proximity, with their times axes arranged vertically. Reflection events may then be traced across the section by correlating pulses from seismogram to seismogram and in this way the distribution of surface. Reflectors beneath the survey line may be mapped. The choice of parameters governing the display of interpolation trace is critical for the final appearance of the section and for its interpretation (fig. 39). The simplest method is to show the data as **a wiggle trace**, where:

- The displacement from the centre line of the trace represents reflection **amplitude**, and
- **Polarity** is expressed by deflection to the right or left of this baseline.

Alternative to the simple wiggle are: (i) the variable area format, or (ii) the variable-intensity. Conventional seismic commonly uses the combination **"variable area and wiggle trace"** display, in which wiggle traces are superimposed on to variable area or sometimes variable-density display (fig. 41). On the interpretation of a seismic data, interpreters are tempting to envisage seismic sections as straightforward images of geological cross-sections, however they should not forget that:

1) The vertical dimension is time and not depth.

Indeed, on the seismic line illustrated in fig. 42, it is important to notice:

a) The vertical scale is **in time**.
b) The horizontal scale is **metric**.
c) **Seismic surfaces** defined by **reflection terminations**.
d) The **substratum** is an old folded belt.
e) The geological global context is that of **episutural basins**.
f) Above the substratum, there is a **back-arc basin**.
g) The back-arc basin is composed of a **rifting phase** (rift-type basin) and a **sag phase**.
h) Reflectors discontinuities have been interpreted as **fault planes**.
i) The more likely **potential source-rocks** were deposited on the upper part of the rift basins.
j) The **sealing-rocks** are associated with the transgressive interval of the sag phase.
k) The chronostratigraphic calibration is based on the **Vail stratigraphic signature**.

Types of Seismic
Traces Display

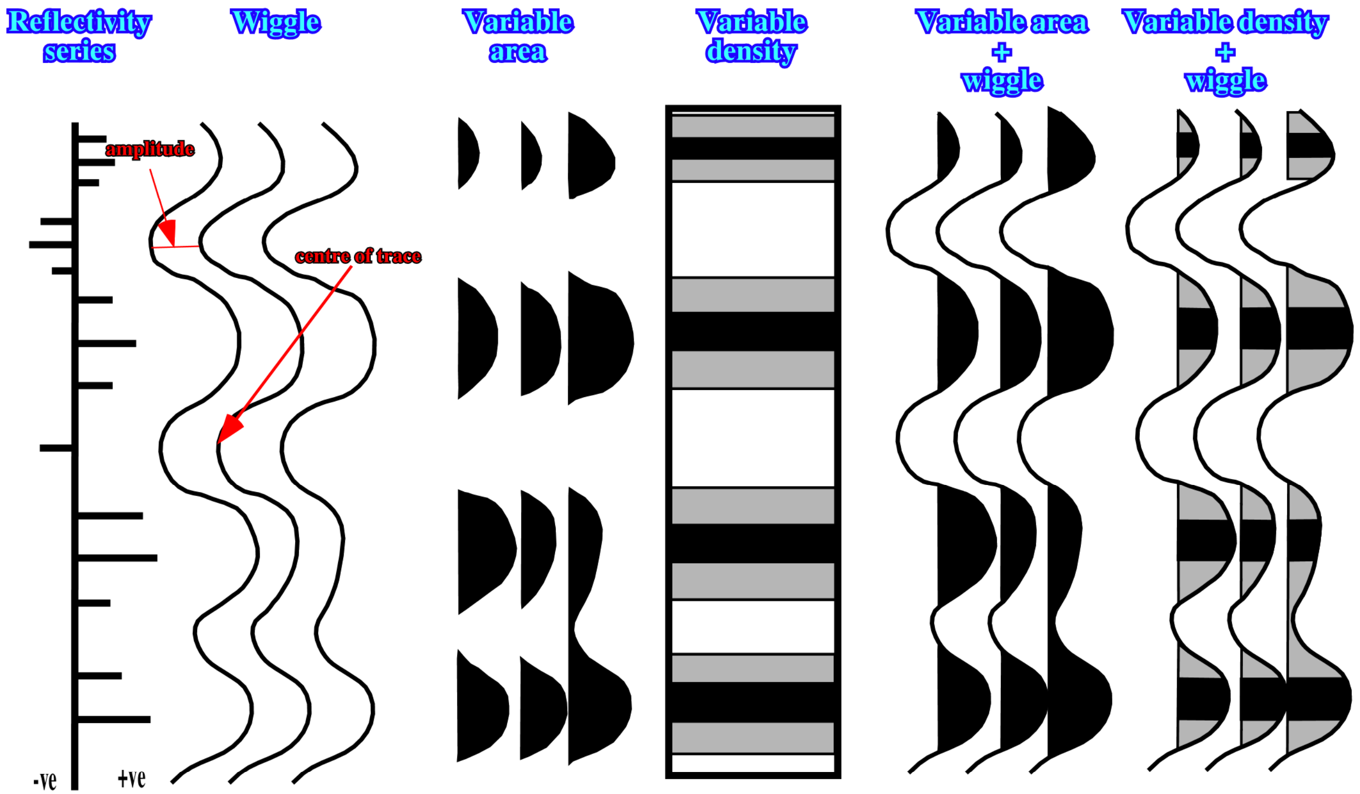

Fig. 41- The simplest display is to show data as a wiggle trace, where the displacement from the centre line of the trace represents reflection amplitude, and polarity is expressed by deflection to the right or left of the base line. In variable area display, there is no continuous trace but the magnitude of associated values is displayed and shaded (usually in black). In variable density display, the variations in reflector strength are indicated by varied shading or different colors. Combinations of different displays are often used. Each display has its advantages and inconveniences.

Interpreted Seismic Line

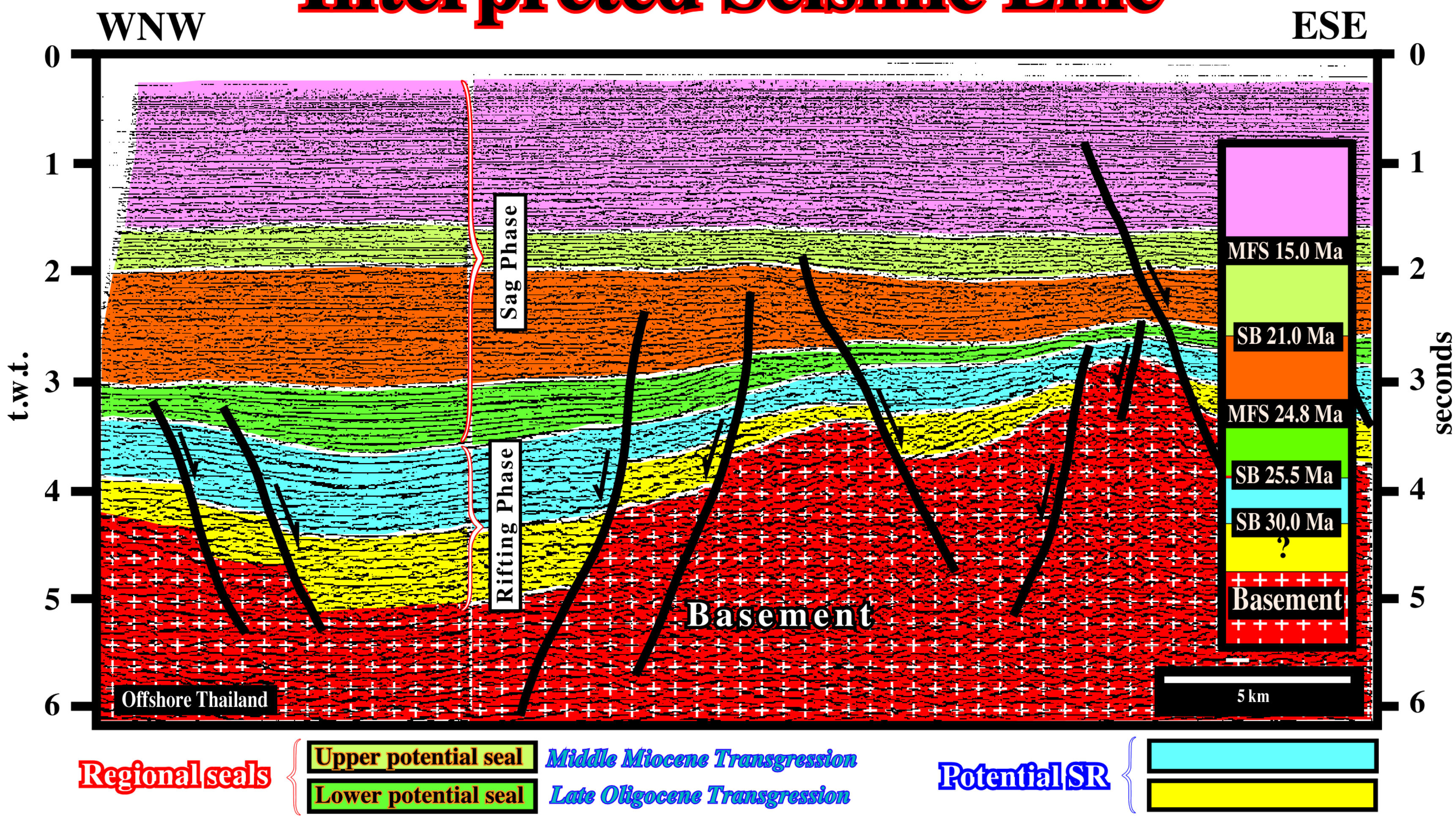

Fig. 42- The interpretation of seismic lines requires the knowledge of the global and regional geological context of the areas where they were shot. Hence, the interpretation of this line, which comes from the offshore Thailand, must fit with the general characteristics of back-arc basins, in which a sag phase overlies a rifting phase. Notice, the vertical scale is in time (two-way times), while the horizontal scale is metric. All seismic markers correspond to chronostratigraphic lines, that is to say, interfaces between relatively thin (50-60 m) sedimentary intervals.

2) The seismic resolution infrequently is higher than 50-60 m.

A key requirement for successful application of seismic stratigraphic principles is a good understanding of the resolution of the seismic method. Generally, geological intervals thinner than 50-60 m are under the vertical seismic resolution (fig. 43).

Single Wavelength

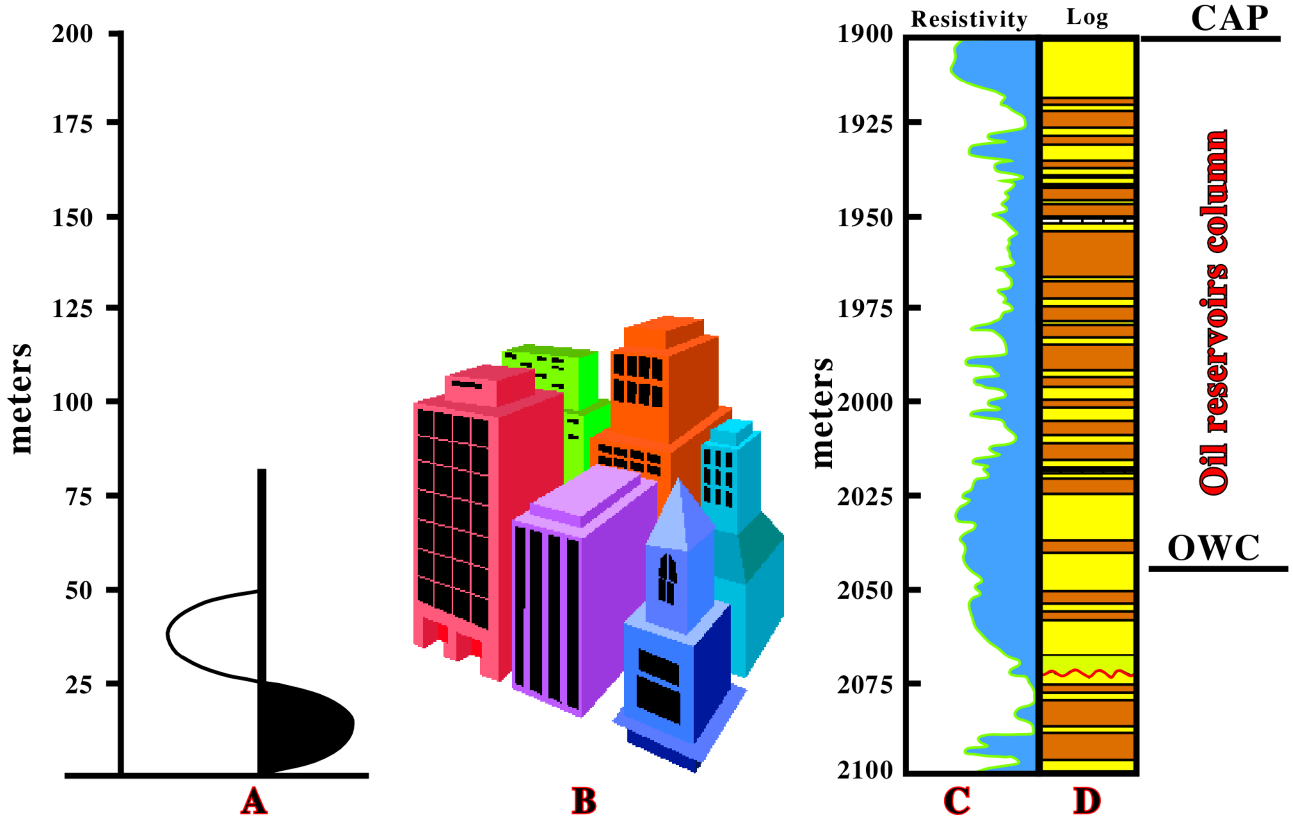

Fig. 43- Vertical comparisons between (A) a single cycle sine wave of 30Hz in a medium of velocity 6000 fps (or 60 Hz; 12000 fps), (B) buildings, (C) geological log through an oil field. Therefore, interpreters must be quite careful when proposing the interpretation of small geological bodies, as channels, point bars, etc.

All interpreters need to take into account both vertical and lateral resolution:

- Vertical resolution

It can be defined as **the minimum vertical distance between two interfaces** needed to give rise to a single reflection that can be observed on a seismic section. This is governed by the **wavelength of the seismic signal**.

- Lateral resolution

It is determined by the **radius of the Fresnel zone**, which itself depends on the wavelength of the acoustic pulse and depth of the reflector. Seismic energy travels through the subsurface and comes into contact with the reflecting surfaces over discrete areas much in the same way that a spotlight travel through the darkness and illuminates a particular area. The energy travels as wave fronts, and the region on the reflector, where the seismic energy is reflected constructively, is known as **Fresnel zone**. In non-migrated seismic data, lateral resolution is dependent on:

(i) Seismic bandwidth,
(ii) Interval velocity and
(iii)Travel time to the reflector.

The procedure of migrating seismic data considerably enhances resolution. However, for two-dimensional migration there is still the problem of the line orientation relative to actual dip. This is resolved on 3D data. For migrated data, lateral resolution depends on:

(i) Trace spacing,

(ii) Length of the migration operator,

(iii) Time/depth of the reflector, and

(iv) Bandwidth of the data.

In fact, the frequency of reflected signals decreases with increasing time/depth (t.w.t.). The main causes of this effect are:

A) Absorption

Absorption is essentially a loss of energy by conversion into heat. We can picture this happening on the microscopic scale:

Particle motion during passage of the seismic wave causes grains to slide against one another, and friction between the grains causes energy loss.

In a given rock, there is generally a constant fractional energy loss per cycle of the seismic wave. There is a constant fractional loss per wavelength.

Higher frequencies are attenuated more than lower ones over a given path. High frequencies will be quite strongly absorbed in traversing a path typical of reflection prospecting, leaving a signal whose dominant frequencies are a few tens of Hz. Earth is a low-pass filter.

B) Effect of short-period multiples

On the earth there is a good deal of layering between the source and the deep reflector. A signal can therefore bounce backward and forward between any two reflectors including land surface, seabed and sea surface a number of times, and perhaps arrive back at the receiver at nearly the same time as the deep reflector signal. These secondary signals or multiples must be eliminated from our record. Short-period multiples also cause a decrease of frequency with travel-time.

Briefly, part of the seismic energy is delayed on its path by reverberation between closely spaced reflecting interfaces. Thus an initially sharp pulse (even if we could produce one) will be smeared out in its passage trough the earth, in effect leading to a slow decrease of frequency with depth.

3) Reflections are not always chrostratigraphic lines.

The great majority of the seismic markers correspond to chronostratigraphic lines. Such analogy was recognized by the Exxon geophysicists, which conceived seismic stratigraphy. Peter Vail summarized the origin of the birth of seismic stratigraphy as follows:

"When Exxon in the 60's explored the offshore Portuguese Guinea (now Guinea Bissau) three wells had been drilled. The most landward well had hit the top of major Cretaceous reservoir sand, overlying an unconformity with Paleozoic rocks below. When the second well was drilled down-dip, it was predicted that this sand would be high in the well, but it was actually encountered much lower. As a result, it was a dry well. A similar experience occurred in the third well. Then Exxon explorationists looked at the seismic section, and saw that the reflection from the top of the sand in the first well was two reflection above the reflection of the top of the sand in the second well and even higher in the third well. There was no miscorrelation of the seismic data with the well-logs and the micropaleontologists confirm that the seismic reflections were following the time lines. The pattern correlation of the well-log marker horizons showed that the real physical surfaces cross the facies of time-transgressive rock units, suggesting that the seismic reflections do not follow massive time transgressive formational boundaries where strong impedance occur, but instead they follow the detailed bedding pattern or the real physical surfaces in the rocks. Thus, they cross time-transgressive facies and rock-formation boundaries, which are not continuous physical surfaces. At the time, this was revolutionary basic driving concept. It provided a new driving concept for interpreting seismic data".

However, on a seismic line, it is common to recognize seismic markers that do not correlate with chronostratigraphic lines (fig. 44). Among them, we can differentiate:

- **Multiple reflections, reverberation or simply multiples,**
- **Ghost reflections,**
- **Water layer reverberations,**
- **Short-path multiples,**
- **Long-path multiples,**
- **Bright spots (fig. 45),**

which will be described in next chapter.

Bright Spot & Multiples

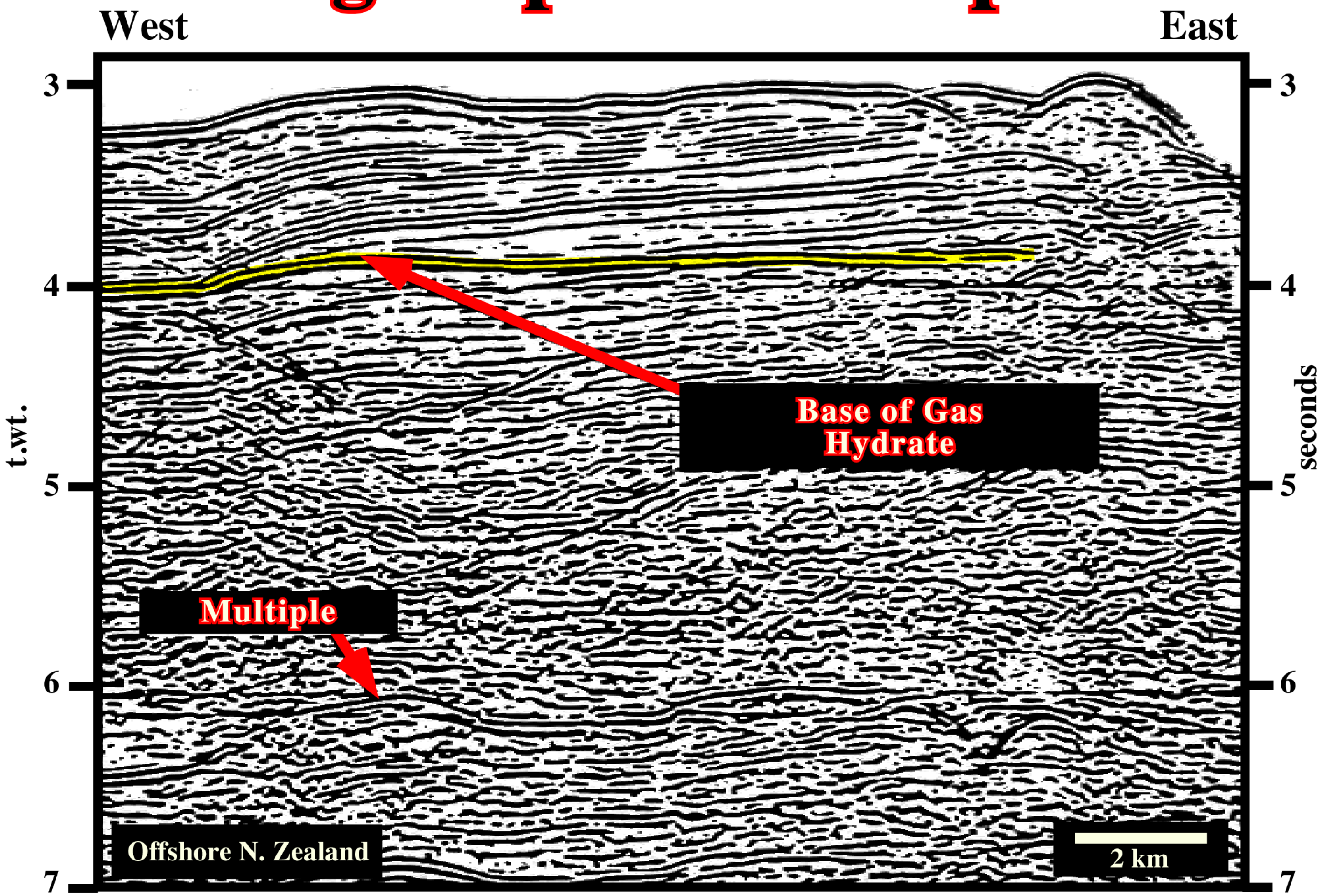

Fig. 44- This seismic line, from offshore New Zealand, shows a bright spot, which can be interpreted as the lower surface of a gas hydrate accumulation (mineral compound CH_4 and water). Basal hydrate reflectors commonly occur in sub-bottom depth, with increasing water depth, because of decreasing temperature of water above the sea floor. At around 6 seconds (t.w.t.) a multiple reflection of the sea floor is quite evident.

Bottom Simulating Reflector
(BSR)

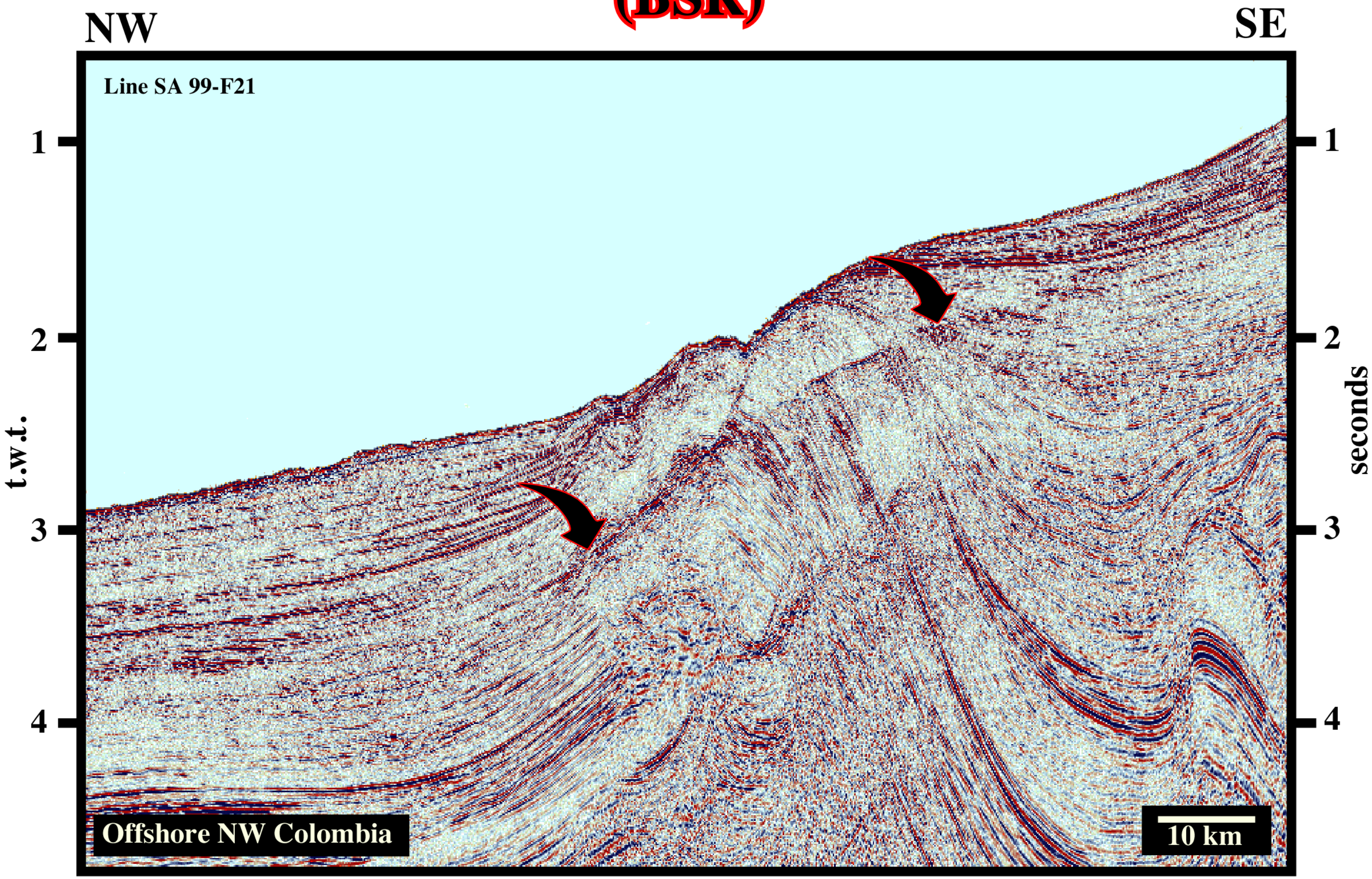

Fig. 45- On this seismic line from offshore Colombia, a bottom simulator reflector is easily recognized. The gas hydrate stability zone (GHSZ) occurs in oceanic sediments over the first few hundred meters below seafloor. In this zone, any methane from organic material, including any seepage from below, is converted into solid hydrate, and is locked in place in the sediments. The origin of the methane is poorly understood, with even its biogenic origin being challenged.

Particular care must be taken to distinguish **gas hydrates bottom reflectors** from ordinary **seabed multiples** (fig. 42). In this subject it is interesting to summarize the composition, occurrence and economic significance of gas hydrates (Selley, R., 1998):

- Gas hydrates are compounds of frozen water that contain gas molecules.
- The ice molecules themselves are referred to as **clathrates**.
- Physically, hydrates look similar to white, powdery snow and have **two types of unit structure**.
- Gas hydrates occur only in **very specific pressure temperature conditions**. They are stables at high pressures and low temperatures, the pressure required for stability increasing logarithmically for linear thermal gradient.
- Gas hydrates have been found in the sediments of many oceans around the world. Specifically, they have been recognized from bright spots on seismic lines in water depths of 1000 to 2500 m (North Sea), and in water depths of 1000 to 4000 m (North Atlantic).

Gas hydrates have been attributed to a **shallow biogenic** source however, a **crustal inorganic origin** has been postulated, based on analysis of their carbon and helium isotope ratios:

- It is probable that methane comes from three sources:
  - (i) Some may be derived from the **mantle**,
  - (ii) Some may be derived from the **thermal maturation of kerogen**,
  - (iii) Some may be derived from **bacterial degradation** of organic matter at shallow burial depths.
- The presence of gas hydrates can be suspected, **but not proved** from seismic data.
- The lower limit of hydrate-cemented sediment is often **concordant with bathymetry** (fig. 42).
- The velocity contrast between the gas-hydrate cemented sediment and underlying non cemented sediment is **large enough** to generate a detectable reflection horizon.
- The bottom-simulating reflector (BSR) may appear as a **bright spot**, which cross cuts bedding-related reflectors.
- The presence of gas hydrates can only be proved, however, by engineering data. They have high resistivity and acoustic velocity, coupled with low density.
- Detailed studies have been carried out on 12 selected areas of known gas occurrence. These studies have revealed that these areas contain well in excess of 100.000 Tcf of gas within the hydrate cemented sediment, and more than 4.000 Tcf of gas trapped beneath the hydrate seal (Selley, 1998)

Estimated Gas Resources in Gas Hydrates

(Krason, J, 1994)

Area studied	1 m hydrate zone (Tcf)	1 m hydrate zone (m^3)
Offshore Labrador	25	0,71 T (10^{12})
Baltimore Canyon	38	1,08 T
Blake Outer Ridge	66	1,88 T
Gulf of Mexico	90	2,57 T
Colombia Basin	120	3,42 T
Panama Basin	30	0,85 T
Middle America Trench	92	2,62 T
Northern California	5	0,14 T
Aleutia Trench	10	0,28 T
Beaufort Sea	240	6,85 T
Nankai Trough	15	0,42 T
Black Sea	3	0,08 T

- Unfortunately, gas hydrates present considerable **production problems** that have yet to be overcome. These problems are due, in part, to the low permeability of the reservoir and, in part, to chemical problems concerning the release of gas from deep crustal zones.
- Clathrates deposits may be of indirect economic significance, however, by acting as **cap rocks**.
- Because of their low permeability, they **form seals** that prevent the upward movement of free gas.
- Some gas is produced from gas hydrates in western Siberia, where they pose some interesting engineering problems.
- Gas hydrates may have considerable importance in **understanding climatic changes**.
- **Relative sea level falls** can induce sudden release of gas may trigger mud volcanoes and pock-marks on the sea bed, pingos in permafrost, as well as large turbiditic currents.
- The huge increase of **greenhouse gas** into the atmosphere may be responsible for the sudden increase in global temperature and carbonate deposition (Gaia Theory).

E) Interpretations Difficulties

When interpreting a seismic line, interpreters must take into account that (i) generally they work with time section and not with depth sections, and (ii) artifacts should remain after, or even could have been generated by seismic processing. Actually, if horizontal and vertical subsurface velocities were everywhere constant, a seismic line section would be the exact image of its underlying geological cross-section. However, under such conditions seismic profiles would show no reflections at all. Fortunately the real world is different:

- Firstly, **ground compaction** of stratigraphic layers under their own weight causes velocities to increase naturally with depth.

  The deeper the depth of burial of a geological level the faster is the velocity of propagation of the acoustic waves through it. One second (t.w.t.) of a shallow section, with a velocity of 2000 m/s, represents 1000 m of geological section. Hence, seismic time-sections are progressively squashed from top to bottom.

- Secondly, seismic velocities also depend on horizontal and vertical varying lithology. These variations are super-imposed on the normal vertical distortion due to compaction.

  The only way to view true scale seismic is to convert time-sections into depth sections. This implies a good understanding of the local velocity field and, the use of an iterative velocity model (as for depth migrated).

E. 1) Time sections versus depth sections

In order to understand the difference between a time section (seismic line) and a depth section (geological cross section), let's consider a typical geological model, taken from Kwanza basin (Angola), and based on several wells' results and field cross-sections (fig. 46). It is interesting to note that in this cross-section there are sharp lateral and vertical changes on the velocity of the seismic waves through the sediments:

- Through the sediments associated with rift-type basins, mainly organic rich shales and sandstones, the seismic waves travel at relatively low velocity.

Geological Model

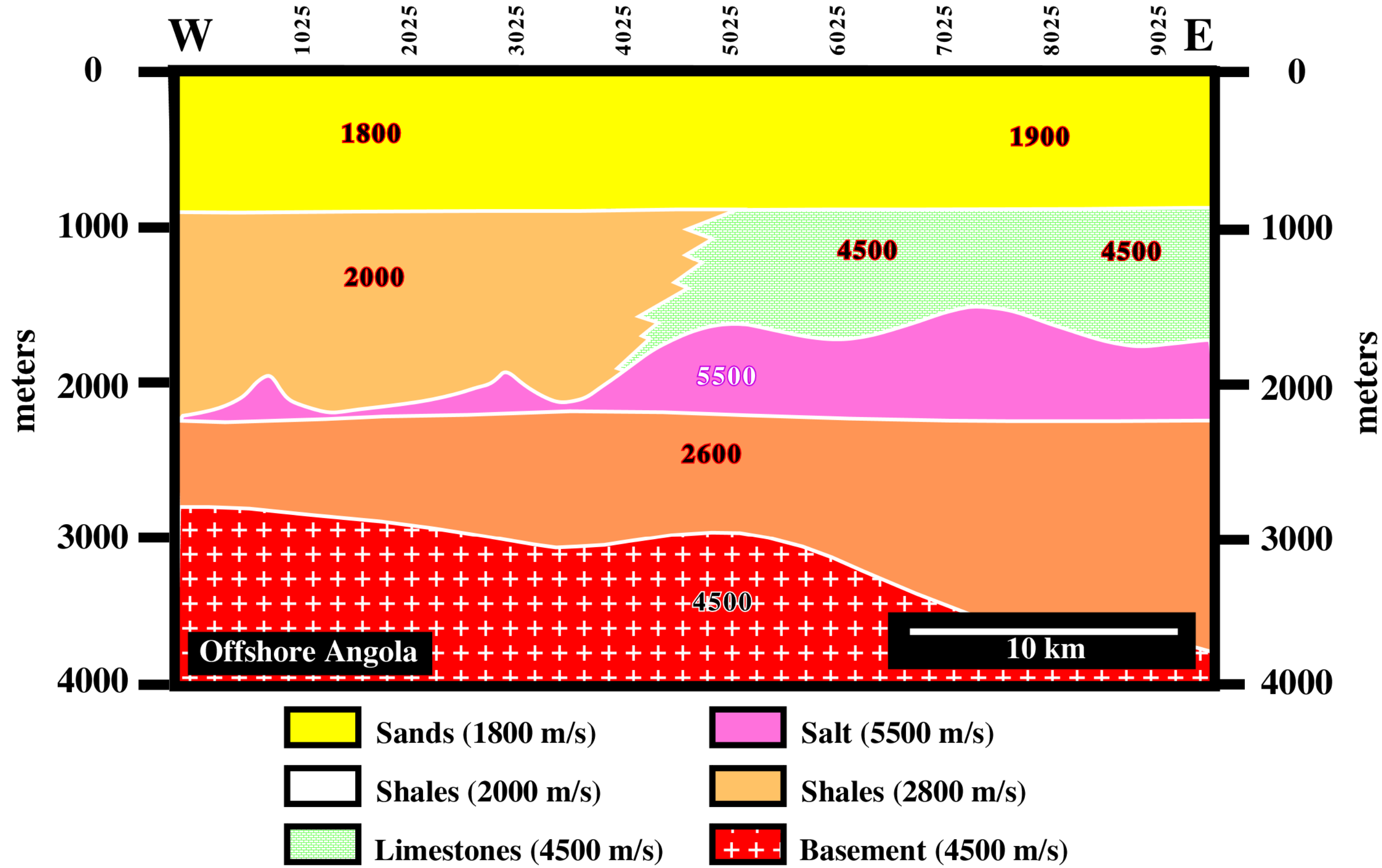

Fig. 1.45- On this geological model, taken from offshore Angola, above the basement (which often corresponds to a Palaeozoic fold belt) rift-type basins were developed during the rifting phase, preceding the break-up of the lithosphere. Overlying the break-up unconformity there is an Atlantic-type divergent margin. A more or less continuous salt layer and a limestone platform were deposited in the lower part of the margin. Subsequently, lateral variations in velocity intervals are quite frequent, as illustrated above. Particularly interesting is velocity change between the platform limestones (± 4500 m/s) and the coeval slope shales (± 2000 m/s), since it induces quite sharp artifacts in seismic lines (see next).

- Overlying the type-rift basin sediments, an evaporitic interval was deposited with a basal limit more or less horizontal but showing significant thickness changes.

- The seismic waves travel through the evaporitic interval with a very high velocity around 5500 m/s.

- Above the evaporites, limestones were deposited in the landward part of the section, whereas in the distal part overpressured slope-shales overly the evaporitic layer.

- Finally, in the upper part of the section, an under-compacted shale-sand interval was deposited (1800-1900 m/s).

- Briefly, the velocity of the seismic waves through these facies are quite different as indicated in fig. 47 (4500 m/s, 2600 m/s; 5500 m/s; 2000 m/s and 1800 m/s). Through the sediments of the type-rift basin, mainly organic lacustrine shales and sandstones, the seismic waves travel at relatively low velocity.

The seismic synthetic response of this geological model is illustrated on fig. 48. It depicts the difference between a geological cross-section (**depth section**) and a seismic line (**time section**). Indeed:

A) Similar interval time thicknesses can correspond to quite different interval depth thicknesses. They are dependent of the velocity of the seismic waves through on each interval.

B) The geometry of the boundaries of the sedimentary packages can be quite different.

C) In time, the base of the evaporitic interval is not horizontal, as indicated the geological model, but strongly deformed by the lateral velocity changes.

D) The top of the basement shows an antiform geometry under the change of facies (limestones /shales).

Let‘s see some real examples: **Example n° 1**

This example comes from the west Palawan offshore (Philippines), where, in the 70’s, several companies explored the conventional offshore (< 200 m):

Time Section

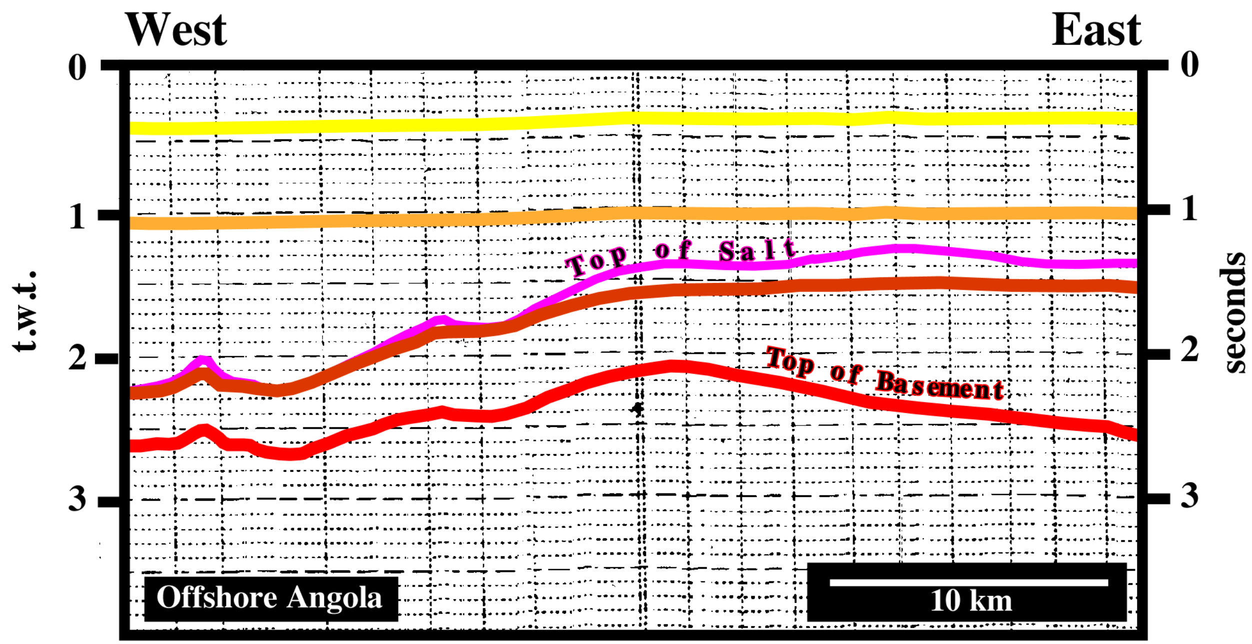

Fig. 48- This time section is the synthetic seismic response (time section) of the geological model illustrated on fig. 47. The red marker corresponds to the interface basement / sediments, that is to say, the top of the basement. However, it does not correspond to a real chronostratigraphic line, but to an unconformity, i.e., an erosional surface. The brown marker fits with the bottom of the evaporitic interval, while the violet emphasizes the top of the evaporites. The light brown and the yellow markers correlate with the bottom and top of the under-compacted shale/ sand interval. The pull-up of the horizon emphasizing the bottom of evaporites (brown marker) is a consequence of the high velocity of the seismic waves through the salt interval. The interval, between the violet and brown markers, corresponds to the limestone platform and slope shales. The high velocity of the seismic waves in the limestones is the responsible for its small time-thickness (eastern part of the time section). In contrast, the low velocity of the seismic waves through slope shales explains their large time-thickness (western part of the violet / brown interval).

(i) One wildcat was supposed to test the hydrocarbon potential of a structural high.

(ii) The structural high was identified on un-migrated seismic lines.

(iii) The seismic line where the well was located is illustrated in the upper part of fig. 49.

(iv) On the seismic line (time), the structural high is located at the vertical of the present limit between shelf and the upper slope environment (abrupt change of water depth).

(v) The structural high was interpreted as a reef anomaly located nearby a shelf break (depositional coastal break is far away landward, the basin has a platform).

(vi) A wildcat was drilled and suspended 200 meters below the apex of the structural high.

(vii) The well‘s results were totally negative. Indeed, no indications of hydrocarbons found and no reservoir or source-rocks have been recognized.

After the negative results of the wildcat, a depth-migration of a few seismic lines line was performed. A depth-time conversion of the line where the well was located is illustrated in the lower part of fig. 49.

Comparing the two versions, explorationists readily understood:

The time-structural high corresponds to a seismic artifact induced by the water depth change and facies change in the overlying sediments.

Example n° 2

The example, shown on fig. 50, comes from offshore Tunisia. It is a nice example to illustrate what interpreters should not do when assessing expected producing reserves in an oil or gas accumulation. In other words, interpreters should never forget:

Time versus Depth

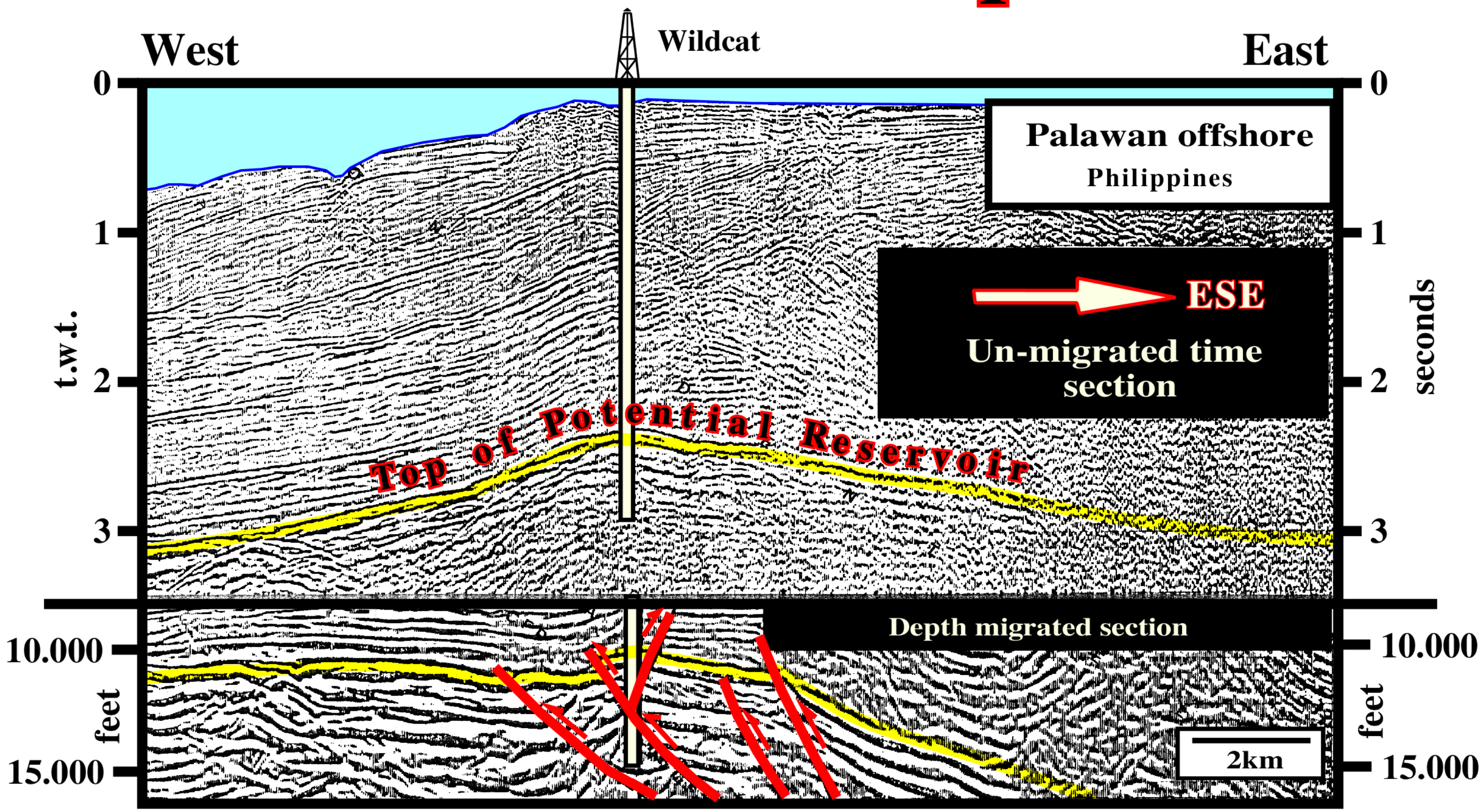

Fig. 51- In the upper part, an un-migrated time version of a seismic line is illustrated, where a wildcat was located. In the lower part, the depth migrated version of the potential reservoir-interval. The depth version strongly suggests that the time-structural high corresponds to a seismic artifact and not to a real antiform structure. In other words, the prospect is not a structural trap, but a morphological trap by juxtaposition. Indeed, explorationists not only forgot the west Palawan offshore is located within the Meso-Cenozoic megasuture, that is to say, located in a compressional geological setting, but also they did not take into account that an increasing water-depth induces an increasing pull-down of the seismic horizons.

a) The difference between a seismic line and a geological cross section. A seismic line corresponds to a time-profile, while a geological cross section is a depth-profile with, or without, vertical exaggeration.

b) To test the proposed geological interpretations of a seismic line. That the more coherent and likely the geological interpretations are, the more difficult they are to falsify.

In fact, the philosophy of seismic interpretation, as well as other geological interpretations, can be summarized as follows:

(i) At the beginning, explorationists have a **"problem"**, generally to find oil.

(ii) So, they propose a **"hypothesis"** (interpretation).

(iii) Then, they try **"to refute the advanced hypothesis"** with new or old observed data.

(iv) Arriving to this point, two possibilities can be considered:

a) The refutation test failed. Hence, with the available data, the hypothesis (interpretation) can be considered as probable. The hypothesis is corroborated by the available data.

b) The interpretation is refuted. In this case, again the interpreter gets a new **"problem"**. The new problem implies a changing of the **"initial hypothesis"**. A **"new hypothesis"** must be advanced, which afterward must be **"tested"** and so on.

This scientific approach by trial and error is the best way to make substantial progress in geological sciences and particularly in seismic interpretation.

Our next seismic example is shown on fig. 50. Again, it illustrates the same typical seismic pitfall:

The highest time structural point of a seismic marker does not necessary correspond to the highest depth structural point.

Structural Highs

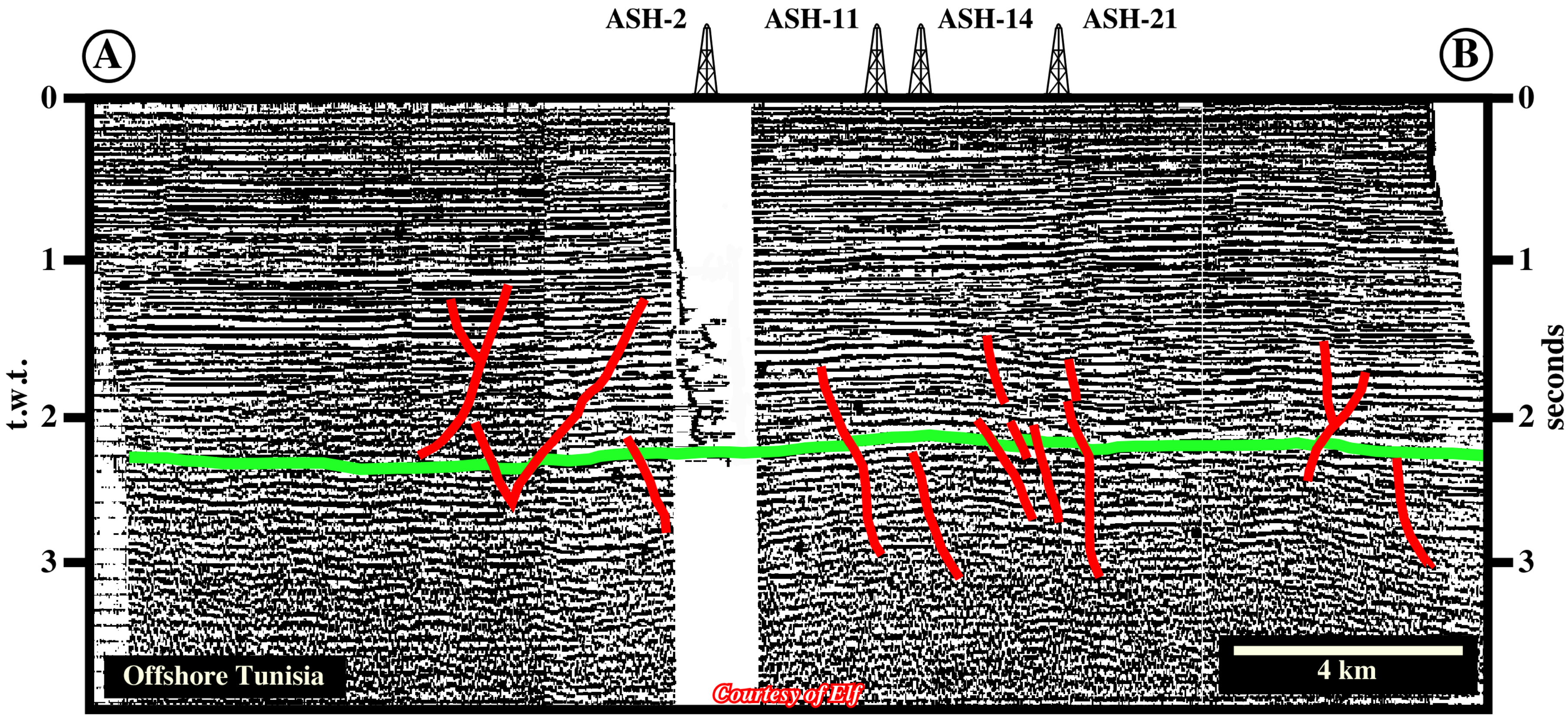

Fig. 50- Take note this seismic line comes from the offshore Tunisia, that is to say, from an area located inside of the Meso-Cenozoic megasuture. In addition, the lengthening of the Pangaea sediments seems to have been big enough to breakup the lithosphere creating an oceanization. Briefly speaking, the basin setting is that of non Atlantic-type divergent margins (globally compressional). On this line (time section), it is easy to recognize that the highest time structural point along the picked reflection (green marker) is near ASH-11. However, as shown later (fig. 52) due to lateral facies and velocity changes, this time structural point does not correspond to the highest depth structural point.

Indeed, on a time-seismic line*, not all time-structural high points correspond to depth-structural high points. Explorationists in charge of the offshore Tunisia, using untested geological interpretations of the seismic lines, proposed to their Management time contour maps of the top of the potential reservoir (green marker on fig. 50), in which a small structural closure was visible (fig. 51). The Management decided to test such a structural closure. The results of the well were positive, i.e. hydrocarbons were found on the predicted reservoirs.

After drilling, explorationists took the positive results of the wildcat as a **"verification"** of the geological interpretations of the seismic lines. Such an attitude is highly dangerous, since the consequence can be catastrophic to the exploration of the area.

In fact, a geological interpretation can never be "verified" (in Latin *verus* means true). Indeed:

> **True geological interpretations do not exist**. The verification of a geological interpretation is impossible. Interpretations can be either **corroborated** or **validated**, by certain data, but that does not mean the interpretations are true.

Following this erroneous attitude, several wells were proposed and drilled with successful results and a development phase took place. At that time, before the drilling of ASH-21, the structural sketch of the field at the reservoir level, assumed by the explorationists was similar to that illustrated in fig. 51. Actually:

- Before the drilling of ASH-21, the converted seismic depth map calibrated with the wells' results (fig. 51), indicated the highest structural point slightly (800-1000 m) eastward of ASH-14, as shown in the cross section AB (fig. 51).

- The well ASH-21 was proposed and the predicted depth of the top of the reservoir interval was at 2744 meters depth.

- The well was drilled and, surprisingly, the top of the reservoir interval was found 100 meters higher. The apex of the structure was not located 800-1000 m westward of ASH-14, but around 1000 m westward of the well ASH-21.

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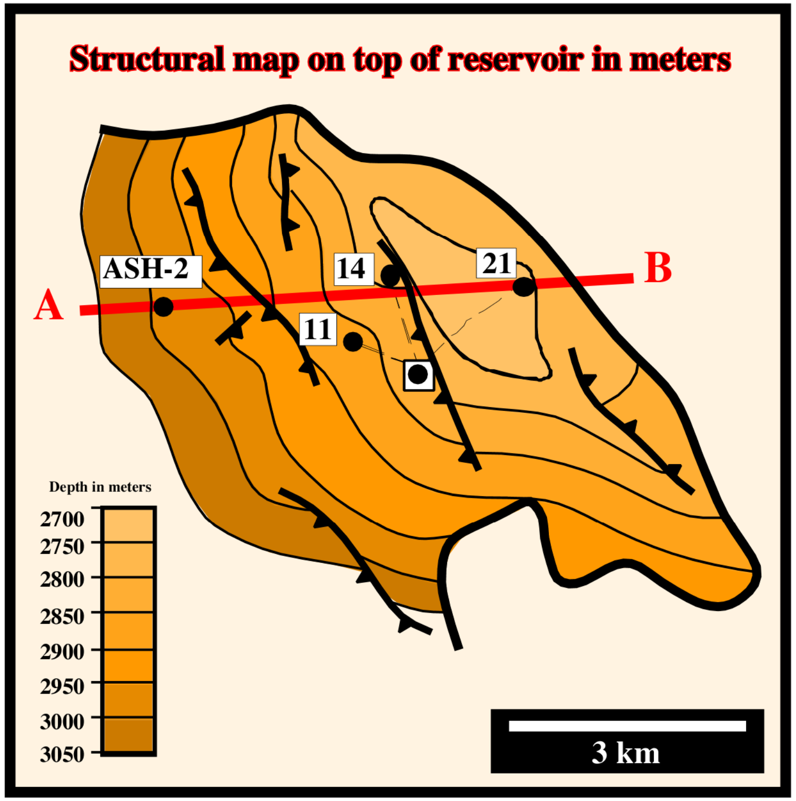
* From now on, a seismic line expresses a time-seismic profile.

Structural Highs



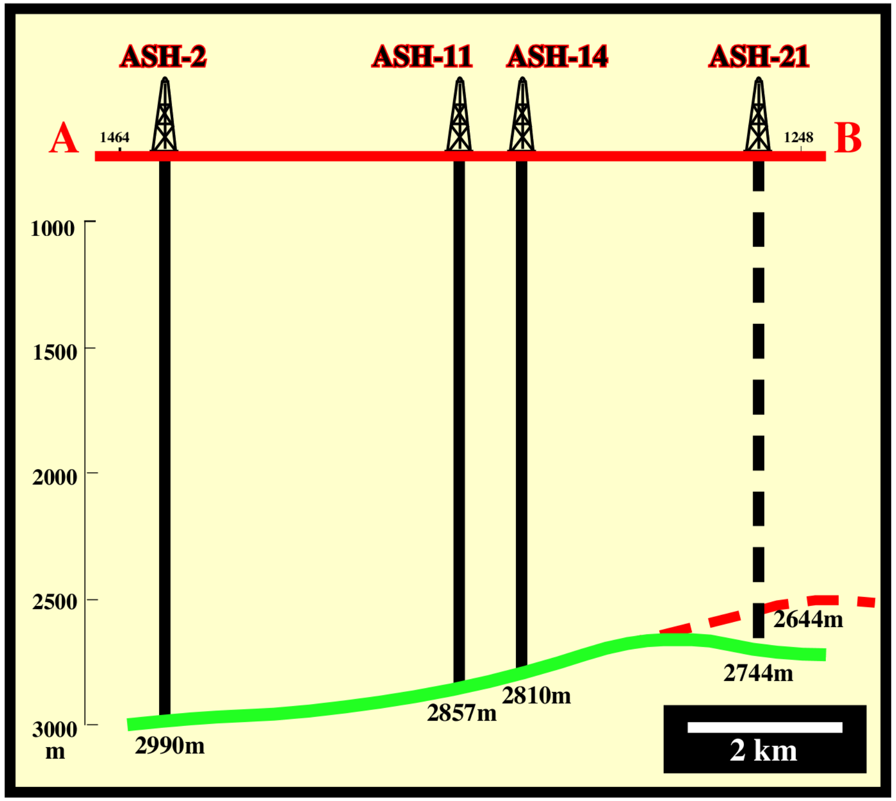


Fig. 51- Before the drilling of well ASH-21, the depth contour maps of Ashart field were similar to the one illustrated on the right of this figure and the structural sections of the reservoir-rock (in green) as the one illustrated on the right. The highest structural point was located westward of ASH-14, eastward of the proposed location of ASH-21. However, the results ASH-21 indicated the actual highest depth point was located westward of ASH-21, at 2644 m (in red). These results completely refute the proposed time geologic interpretations of the field, which, by the way, were mainly based in the picking of the top of the reservoir interval. Indeed, as shown next, it seems explorationists forget that a particular interpretation (picking just one marker) must fit within the global geological picture. Actually, in Geology, and particular in Petroleum Geology (Petroleum Systems), explorationists progress from the general to the particular and not from the particular to the general.

The substantial increasing of the hydrocarbon “reserves” following the drilling of ASH-21 masked the mistake made by the seismic interpreters. Nevertheless, the understanding of the surprising results of well ASH-21 became extremely important in order to avoid future mistakes. Actually:

a) The interpreters forgot a seismic line is **a time section** and not a **depth section.** Also, they forgot that lateral lithological changes must be taken into account in the interpretation.

b) Lateral lithological changes induce lateral velocity changes, which, in a depth section, can invert the relative position between two points.

c) In a time section, a relatively high structural point can become a relatively low point in a depth converted section, as a function of the interval velocities.
ing the seismic line illustrated on fig. 50 in sedimentary packages and not just following single and more or less continuous reflections, explorationists quickly recognize a sedimentary interval between 1.5 and 1.75 seconds in the left part of the line (coloured in green on fig. 52):

- This sedimentary package **thins leftward** and becomes **very condensed** near the location of ASH-21.

- Such a geometry is associated with a transgressive episode, which deposits thickens landward as the depositional coastal break backsteps and the water depth increases creating a larger shelf (platform).

In fact, interpreters should have recognized such a lateral facies change:

- Seaward of the Oligo-Miocene shelf break (abrupt dip change in the green interval), the platform limestones are gradually replaced by more or less coeval slope shales.

- This change in lithology (facies) induces a seaward slowing of the interval velocity.

- Below the condensed limestones, near the ASH-21, seismic waves are delayed and the associated reflections (time) are pull-down relative to those underlying the thick limestone package on the central and right part of the seismic line, which are pulled-up.

Structural Highs

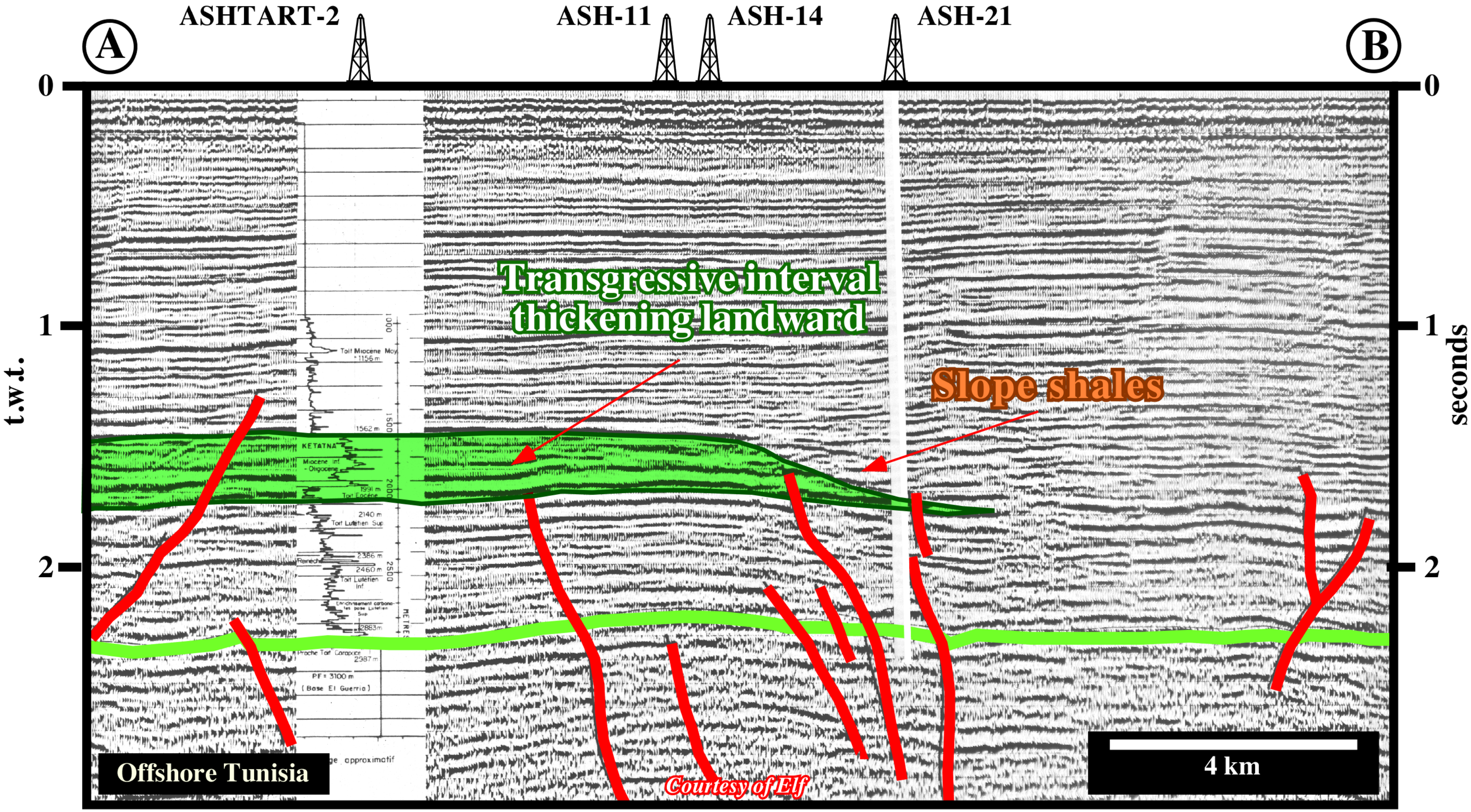


Fig. 52- This line corresponds just to an enlargement of the line illustrated on fig. 50. It shows a transgressive backstepping interval (in green) thinning seaward. Such a thinning corresponds to a lateral change in facies and velocity. The different time thickness of this transgressive calcareous interval, drilled in ASH-2 and ASH-21, readily explains why the highest time-structural point of the potential reservoir (lower green marker) does not match with the highest depth-structural point: the seismic waves do not travel at the same velocity in limestones and slope shales. The markers below the slope shales will be pulled-down.

E. 2) Un-migrated versus Migrated Profiles

Multifold covered data display implies a geometrical approximation (fig. 53):

Source and receivers positions are removed artificially and placed on a same location by applying dynamic (or move out) correction.

- **When a reflector is tilted, the reflectors paths arriving at two receivers, located at equal offsets up-dip and down-dip from a central shot point, are of different length, so the rays will therefore have different travel times.**
- **Dip move out is defined as the difference in travel times t_x and t_{-x} of rays reflected from the dipping interface to receivers at equal and opposite offsets x and -x.**
- **The steeper a reflector is the greater is its misllocation on an un-migrated time section.**

Dip Move Out Correction

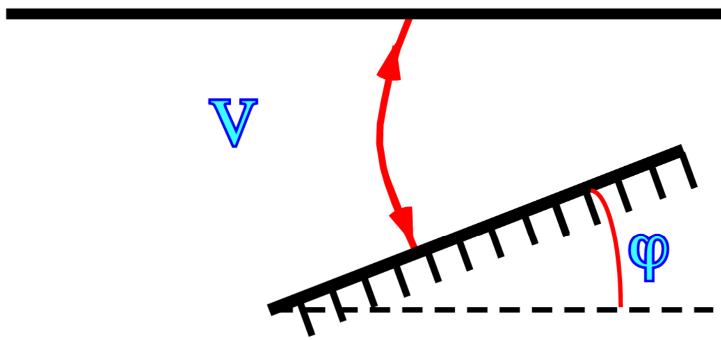


Fig. 53- Dip move out may be used to compute the reflector dip φ if V (average velocity) is known. V can be derived by a mathematical equation using the NMO (normal move out, i.e. the difference between the travel times t_1 and t_2 of reflected ray arrivals recorded at two offset distance x_1 and x_2), which for small dips may be obtained with sufficient accuracy by averaging the up-dip and down dip move-outs.

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Migration (fig. 54) is the process of reconstructing a seismic section so that reflection events are repositioned under their correct surface location and at a corrected vertical reflection time. In order to migrate a seismic section accurately, it would be necessary to define fully the **velocity field** of the ground, i.e. to specify the value of velocity at all points. In practice, for the purposes of migration, an estimate of the velocity field is made from **prior analysis** of the non-migrated seismic section, together with information from borehole logs.

Migration also improves the resolution of seismic sections by **focusing energy spread over a Fresnel zone** and by **collapsing diffraction patterns** produced by point reflectors and faulted beds.

In addition, migration removes the **diffracted arrivals** resulting from point sources, since every different arrival is migrated back to the position of the point source.

Migration Target

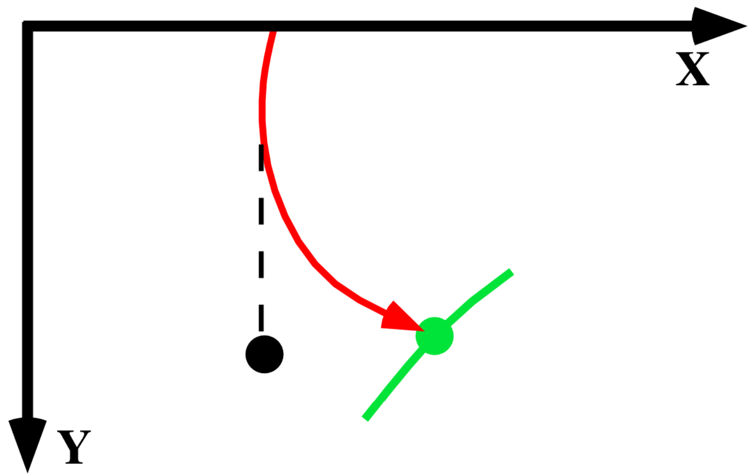

Fig. 54- For a given reflection time, the reflection point may lie anywhere on the arc of a circle centred on the source-detection position. On a non-migrated seismic section the point is mapped to lie immediately below the source-detector. In a migrated line the point is repositioned under its correct surface location and at a corrected vertical reflection time.

Although, nowadays, the majority of the seismic lines used in petroleum exploration are migrated lines, it is interesting to make a review of the major differences between migrated and un-migrated data in order to understand not only the evolution of geological interpretation of seismic profiles, but the organization of the exploration teams as well.

A) Antiform Structures

Since a seismic section presents its trace vertically below the observation point, it is evident that the seismic line will portray antiform structures a **little wider** than in the ground (fig. 55). In other words, the **flanks of the structures are less steep**. However, the crest of the structure is always in its correct positions with respect to the surface. Hence, crestal areas, with their low dips, are the least distorted areas.

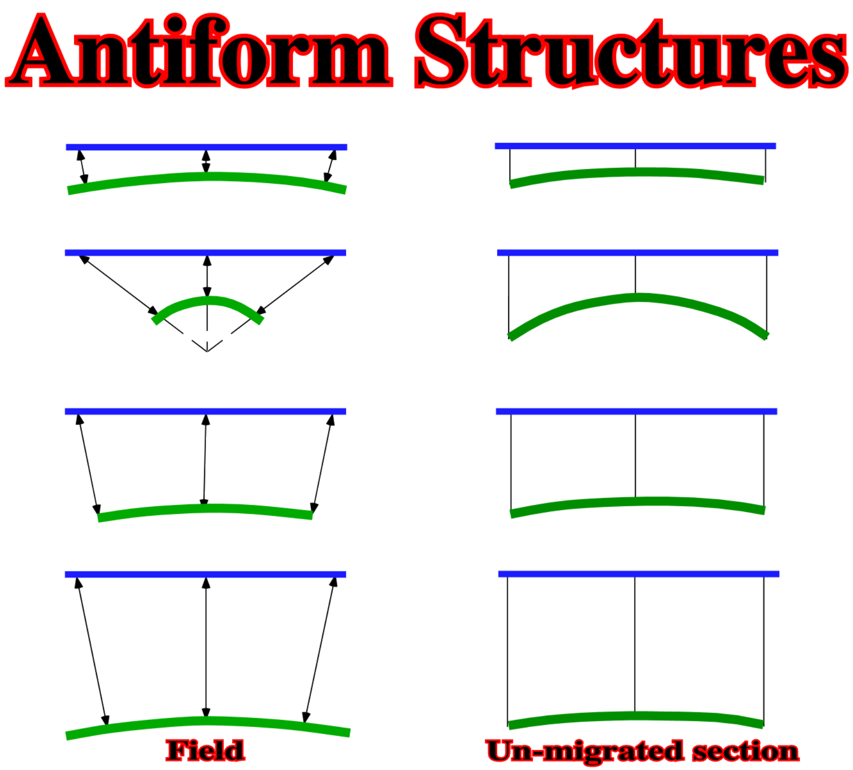

Fig. 55 - These sketches illustrate the seismic responses of antiform structures with different geometries. It is easily to notice that on un-migrated seismic lines the closed surface associated to antiform traps is always overestimated. Indeed, in the 70‘s, before the migration advent, the misunderstanding of this important feature could have catastrophic consequences. I remember quite well, as the majority of the large, and apparently economic, prospects of Labrador Sea (based in un-migrated data) disappeared, as the first migrated versions of the seismic lines were performed.

The seismic answer of real earth antiform structures (anticlines and roll-overs) on un-migrated seismic lines (fig. 55) was summarized as follows (A. Fitch, 1979):

(i) A gentle antiform is scarcely changed in its seismic expression.

(ii) A sharply folded, narrow antiform may have seismic expression as a gently folded, wide antiform.

(iii) The antiform will show **less relief** on the seismic response.

(iv) A given antiform shape will have a wider seismic expression the **deeper it gets**.

(v) Concentric anticline folds are **parallel folds** on seismic lines.

(vi) Widening in depth of parallel folds can progress to the point where neighbouring anticline folds can overlap in their seismic expression.

B) Synform Structures

Gentle synforms present few problems. Synforms become a **little narrower** on seismic than they are in fact. The lower point of the synform is undisturbed. A. Fitch (1979) summarized the seismic response (fig. 56) of a concentrically synforms as follows:

- **Concentric** synforms appear as **parallel folds** in the seismic response.

- With **parallel folding** in the real earth, **the deeper** the synform reflector considered **the narrower** its seismic response.

- **A depth is reached**, eventually, at which the seismic response of the whole synform is **a single bright point**.

- Below this level, the normal to deepest part of the synform is **shorter** than the normal to any point on the flanks of the synform, that is to say, the seismic response of such synform is **convex upward**, that means it looks like an antiform at first glance (fig. 57).

Synform Structures

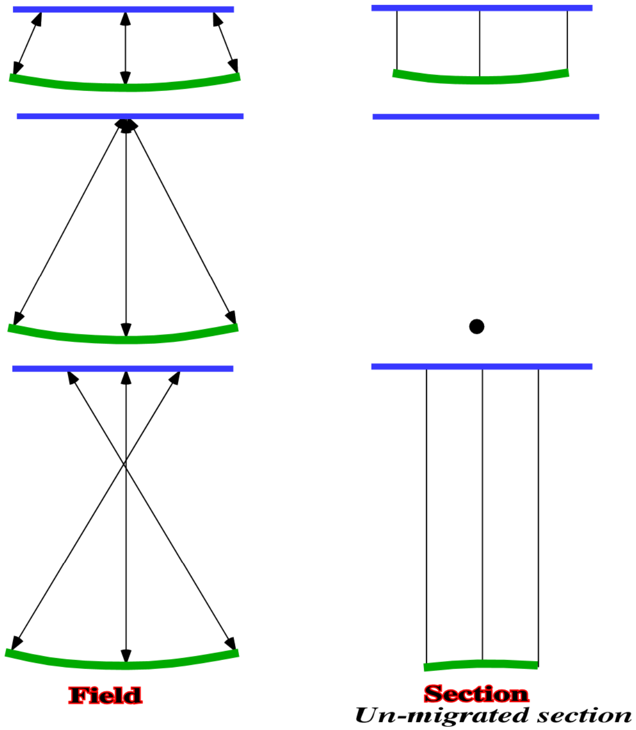

Fig. 56-The illustrated relationships can be stated in terms of the position of the centre of curvature of a cylindrical real synform (field): (i) when the centre of curvature is above the surface, the synform response is concave upward; (ii) when the centre of curvature is at surface, the response is a point and (iii) when the center of curvature is in the subsurface, the synform response is convex upward.

C) Complex Structures

Intrusive bodies create complex structures that have seismic responses that are often difficult to interpret. The intrusive material may be: salt, mobile shale, or volcanic. As, in many cases, sedimentary beds are strongly folded around the top of the intrusive body, **droopy hyperbolas** obscure the flank structures deeper down.

In most cases, intrusive bodies have a piercement relationship, hence sedimentary beds, which are cut across, show typical fault features. Salt domes, being usually flanked by rim synclines, form very complex structures (fig. 57), which yield seismic responses that, at first, seem unrecognizable.

Complex Structures

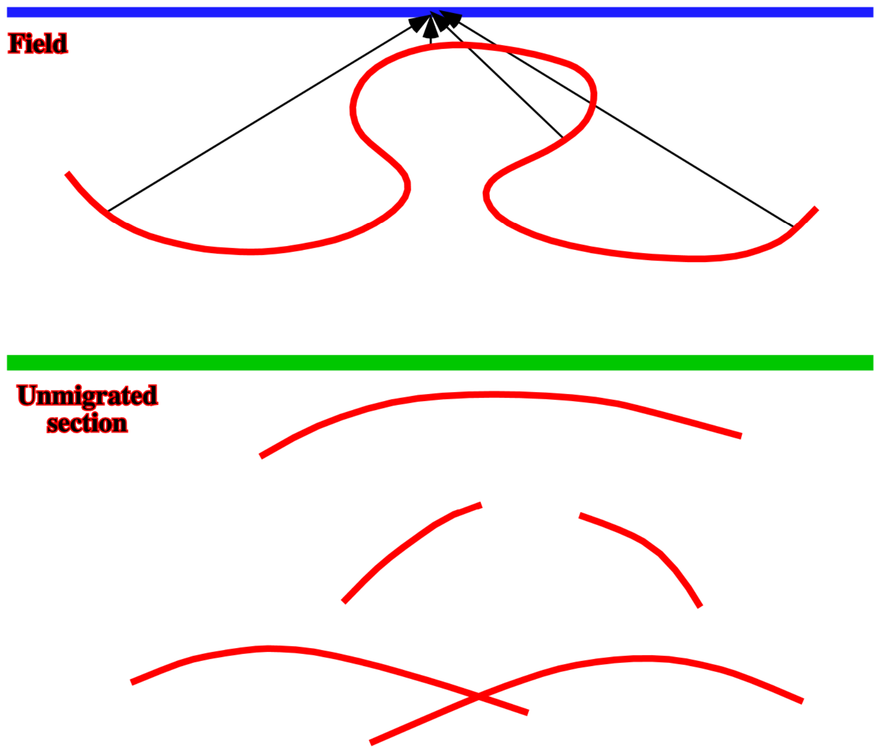

Fig. 57- Complex structures such as those associated with salt diapirism are very difficult to interpret in un-migrated seismic data. However, as we will see later, geological knowledge of salt tectonics and few migrated lines are usually sufficient to interpreted complex halokinetic structures.

Geological knowledge is absolutely necessary to perform good seismic interpretations, particularly in complex tectonic areas. However, several years ago, seismic interpretation was the realm of geophysicists trained in seismic processing but without geological knowledge. When I was a young geologist, just very few geologists were allowed to use seismic lines. I can never forget, when I asked authorization to attend an internal Exxon short course with P. Vail as instructor. My boss was extremely surprised. For him (a geophysicist), a geologist attending such a course, was a loss of time. So, I was obliged to use seven days of my annual vacation to attend the course.

Let's see some real seismic examples:

Ex: 1- Un-migrated seismic line:

Before the advent of migration processing, i.e. before the 80's, explorationists were obliged to interpret, in structural and stratigraphic terms, un-migrated lines such as the one illustrated below (fig. 58).

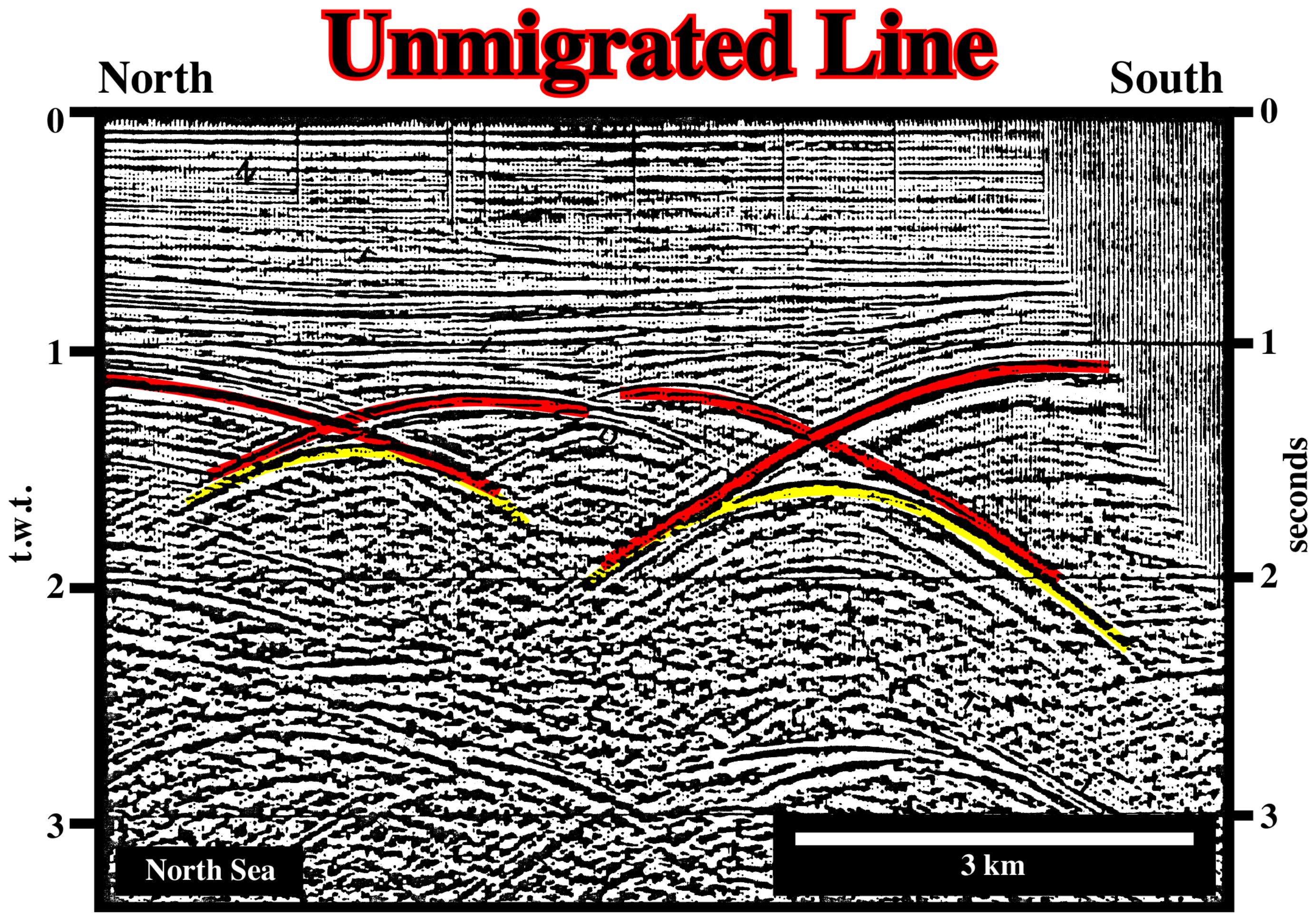

Fig. 58- This old un-migrated seismic line comes from a relatively quite tectonic North Sea area. Knowing the regional geological setting and the fact that a synform seismic response can be a convex upward reflection (when centre of curvature is in the subsurface, see fig. 56), it is relatively easy to predict on this line two syncline structures (see fig. 59).

Ex: 2- Migrated seismic line

Migration processing was extremely helpfull to seismic interpreters, particularly geologists, since a migrated line looks like a geological cross-section. Comparing the lines illustrated on figs. 58 and 59 is sufficient enough to understand the impact of migration.

Migrated Line

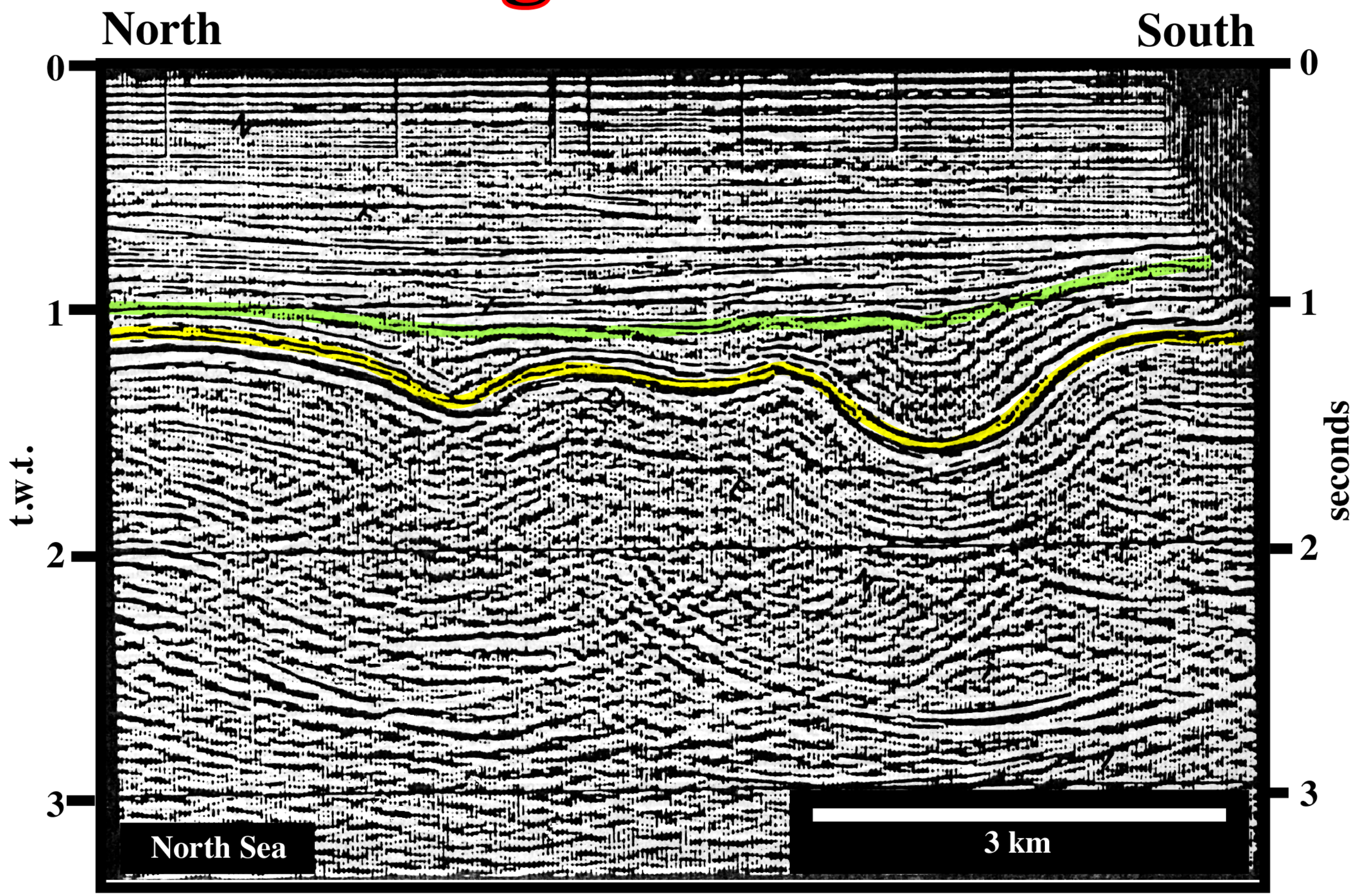

Fig. 59- This seismic line is the migrated version of the previous un-migrated line. In spite of the fact that a migrated seismic line looks like a geological cross-section, interpreters must never forget (i) the vertical scale is in time and (ii) seismic artifacts, as those induced by lateral changes of velocity, are almost always present. In other words, interpreters must differentiate the reflector with geological meaning from those unrelated to the geology of the area.

Since migrated seismic lines became available for interpretation, the organization of the teams in charge of the geological interpretation of seismic data changed drastically due to massive arrival of geologists. At that time, geologists were trained to understand the differences between seismic lines and geological cross sections, in order to avoid misinterpretations induced by seismic artifacts. However, with time, training courses for geologists became rare. Nowadays, the majority of geologists arriving in interpretation teams do not know the driving principles of interpretation. I hope that this seminar can help not only geologists but geophysicists as well.

Ex: 3- Offshore Norway

On the un-migrated seismic line illustrated on fig. 60, the recognition of the different sedimentary basins and stratigraphic phases requires from interpreters a certain ***a priori* knowledge**. The interpretation of such lines depends mainly on the geological knowledge of interpreters:

(i) **Geological context;**

(ii) **Basins classification** (Bally's classification);

(iii) **Driving concepts of Sequential Stratigraphy**, and

(iv) **Driving mechanisms of Seismic Reflection**.

The depth migrated version of the previous line is shown in fig. 61. Its geometry looks similar to a geological cross-section. Geological interpretation is easier than on the previous un-migrated version. This is particularly true for young geologists. However, it must be noticed that:

- **The scales** (horizontal and vertical) **are different**.
- The profile **is not at natural scale** (1:1).
- The **vertical scale is exaggerated**.

As said previously, to migrate a seismic line correctly, it is necessary to define fully the velocity field of the ground, i.e. specify the value of velocity at all points. In practice, for purposes of migration, an estimate of the velocity field is made from prior analysis of the non-migrated seismic section, together with information from borehole logs when available. In spite of this approximation almost invariably migration leads to major improvement in the seismic imaging of the reflector geometry.

Un-migrated Line

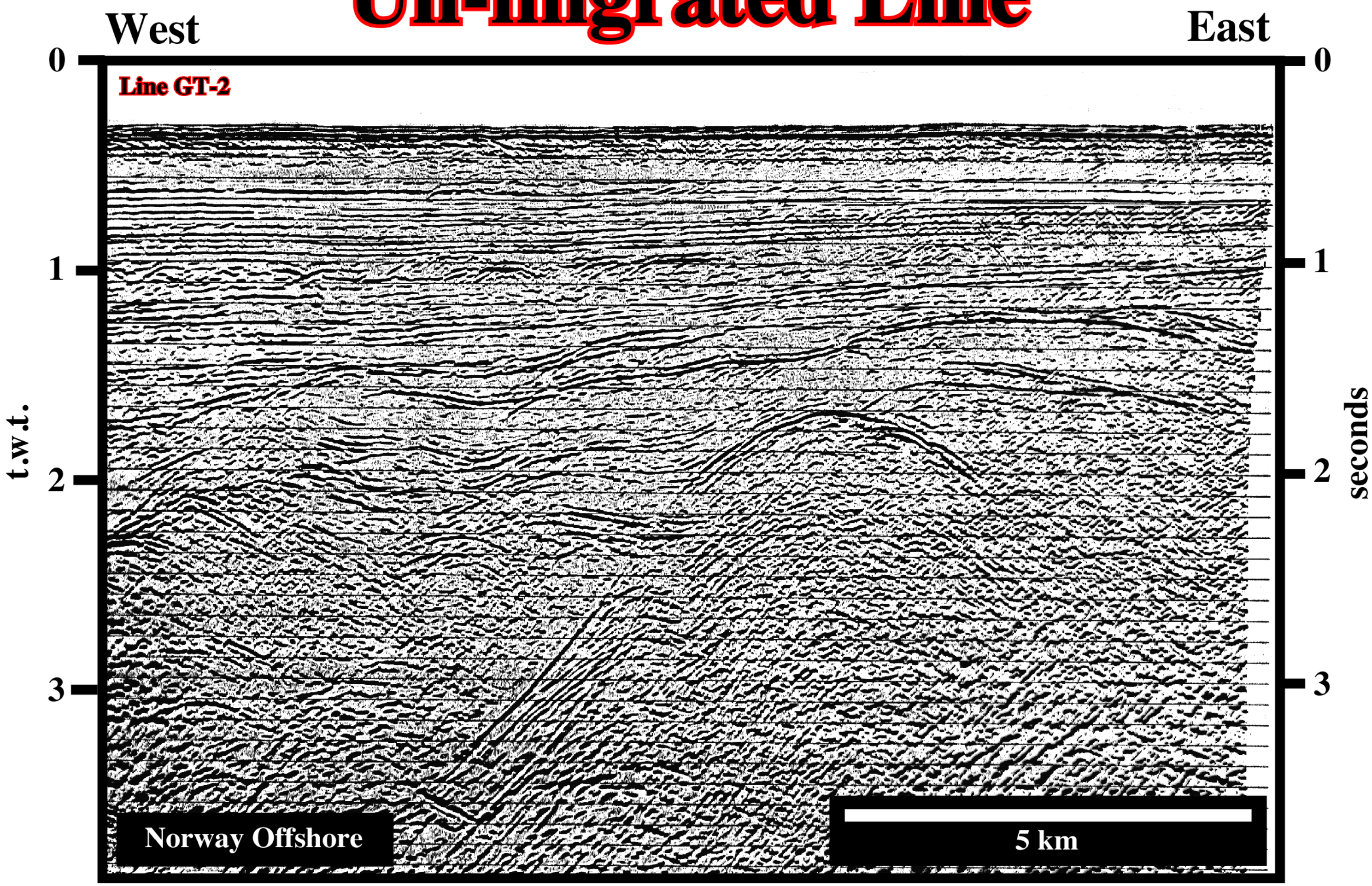

Fig. 60- This old un-migrated seismic line comes from offshore Norway. So,to begin the interpretation, theoretically from bottom to top, interpreters must recognize (i) type-rift basins and (ii) an Atlantic-type divergent margin (following the A. Bally's basin classification). These basins are separated by a major unconformity, which corresponds to the break-up of the Pangaea lithosphere. In addition, in the margin, they must try to individualize the transgressive, that is to say, the backstepping stratigraphic phase and the regressive or forestepping phase. Indeed, interpreters just recognize on seismic lines what they known. In other words, they must progress from the general to the particular and not the opposite.

Depth-migrated Line

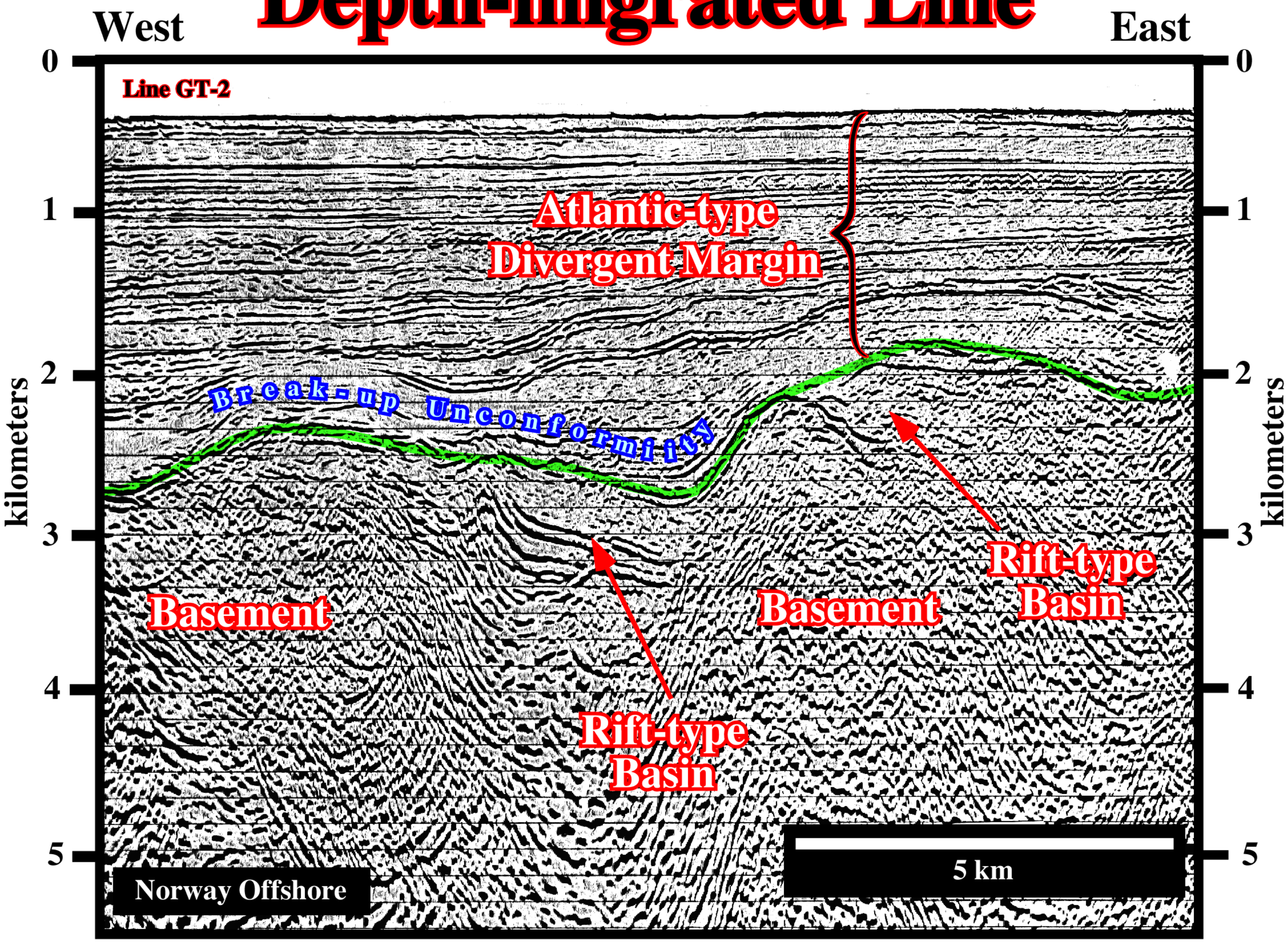

Fig. 61 - This line is a depth migration (65°) version of the line illustrated previously (fig. 60). However, the vertical scale is exaggerated. Hence, interpreters must take into account that geological laws require a natural scale, that is to say, the same vertical and horizontal scales. On this version, the infrastructure (basement), the rift-type basins and the Atlantic-type divergent margin are much more easy to recognize than on the un-migrated version (fig. 60).

Ex: 4- Offshore Angola

- The line illustrated in fig. 62 comes from offshore Kwanza (Angola).
- Salt tectonics induces huge antiform extensional structures, which have been attracted petroleum explorationists since the beginning of the century (Sinclair Oil Company, 1904).
- In the 70's, when only un-migrated lines were available, interpreters had a lot of problems to solve to understand the tectonic complexity induced by halokinesis.
- Nowadays, migrated versions of the old lines and new migrated data, as well as 3D, make interpretation easier. Nevertheless, interpreters must pay attention to potential pitfalls, such as: pull-ups, pull-downs, reflectors' dips, etc., which are often associated with the available data.

The interpretation of the migrated version (fig.63) is easier than the un-migrated version (fig. 62). Actually:

- The majority of diffractions disappeared.
- The reflectors are in a more correct position.
- The vertical scale still is in time. Hence, the dips of the reflectors are apparent and exaggerated.
- Using exaggerated dips as a criterion for predicting facies and environment is dangerous. Indeed, lithological and environment predictions require:

(i) Time depth conversion and
(ii) Data at natural scale, that is to say at 1:1 scale.

Comparing un-migrated (fig.62) and migrated (fig. 63) versions is readily demonstrates that:

(i) Migration removing hyperbolic interferences clarify the reflections.
(ii) Hyperbolic features arising from reflection terminations, faulting or other ways, are shrunk to a point by the migration process.
(iii) Antiform structures have a more naturalistic picture on migrated lines.
 - Apexes are not moved in position.
 - Flanks are more abrupt.
(iv) Fault planes, and associated morphological traps by juxtaposition, are moved up dip by migration, so a better assessment of the potential closed area is possible.

Un-migrated Line

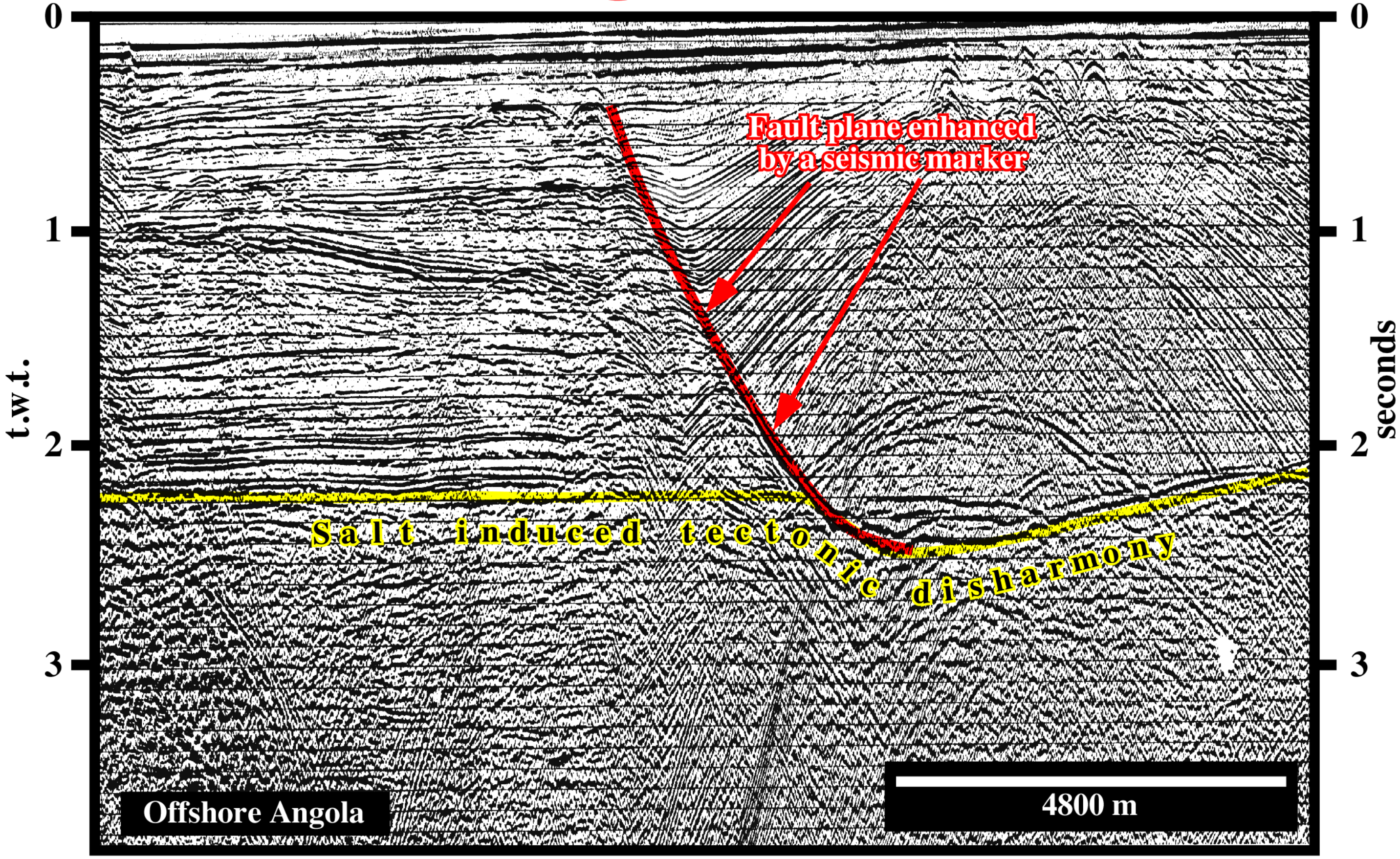

Fig. 62- This old un-migrated line from offshore Angola, where a Cretaceous evaporitic salt layer was deposited near the bottom of the Atlantic-type divergent margin, strongly increases the complexity of the data. Halokinesis, associated with an extensional tectonic regime, developed a sharp tectonic disharmony at the base of the evaporites. The sediments overlying the evaporites are quite deformed, while the infra-salt strata are almost undeformed. This tectonic disharmony does not correspond to a major stratigraphic boundary. In other words, the segmentation of the Atlantic margin sediments into supra and infra-salt strata is a tectonic division. It does correspond to any major stratigraphic feature. The salt induced tectonic disharmony is much more evident in migrated data as illustrated on fig. 63. Notice that the lower part of the major listric fault zone is filled by salt, which is enhanced by a non chronostratigraphic seismic reflector.

Migrated Line

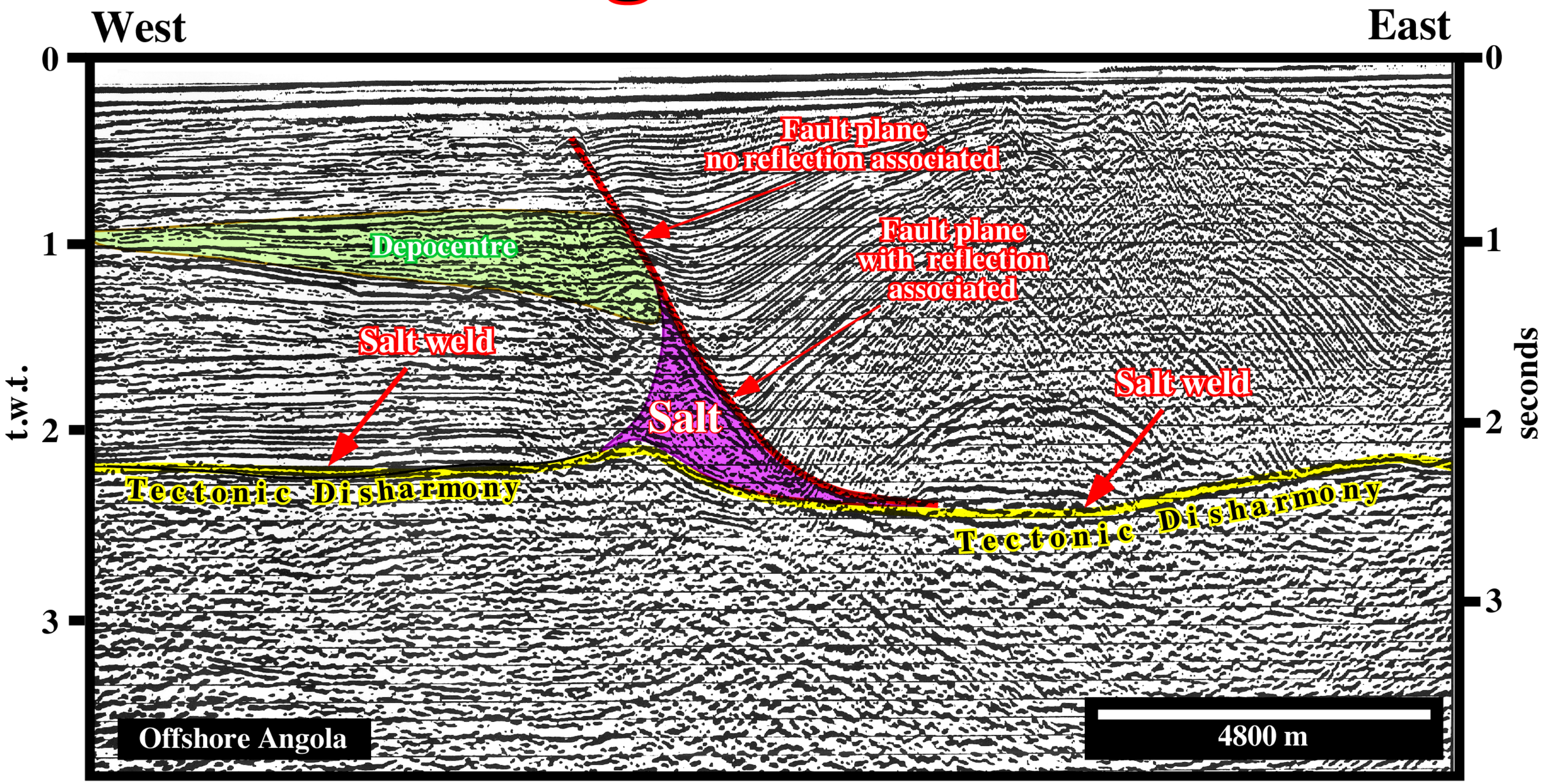

Fig. 63- The migrated version of the previous line, illustrated above, in which the majority of the diffractions have disappeared, depicts much better the seismic surfaces (surfaces defined by the reflection terminations) than the un-migrated version (fig. 62). The tectonic disharmony, at the bottom of the evaporitic interval, is quite evident. Similarly, the geometric relationships and the internal configuration in the extensional antiform, developed in the hangingwall of the listric growth-fault, are readily recognized. Also, it is easy to notice that, at the present time, the evaporitic interval is not continuous. A salt roller (in the lower part of the listric fault) separates two quite evident salt welds. As theoretically expected, the sediments underlying the tectonic disharmony are almost undeformed, which contrasts with the post-salt sediments.

(v) On the un-migrated line, interpreters are left with the impression of faulting, but it lacks precision.

- Most interpreters would hesitate to draw the fault planes.

(vi) On the migrated line, in the central part of the line, interpreters easily recognize an important listric fault with an eastward vergence and a decreasing hade.

- On lower part the fault plane, where the hade is gentle, a seismic reflector is associated with the fault plane.
- On the apex of the large antiform, several fault planes with opposite vergences can be recognized.

Notice that the non-primary reflections, such as
- Multiple,
- Refracted Reflections,
- Reflected Refractions, etc.

are merely distorted by the migration process, so they can mislead the interpreters.

The fig. 64 illustrates a depth-migrated version of the previous line. Notice that:

- The line is at natural scale.
- The horizontal and vertical scales are metric and equals.
- The dips of the reflectors are real.
- Geological laws, such a Goguel‘s law, Walter’s law, etc., must be respected.

On fig. 65, a depth migrated version,is illustrated, with exaggerated vertical scale (2.5 x):

- The dips of the chronostratigraphic lines (primary seismic reflection) do not correspond to the dips of the beds on the ground.
- They are 2.5 times exaggerated.
- Dipmeters values match only with the dips of depth-migrated lines when depicted at natural scale (1:1).

The majority of seismic lines used in interpretation are vertically exaggerated. Under these circumstances, **Anderson‘s Law** of faulting must be used carefully, since on normal seismic data, seismic surfaces associated with fault planes have a much higher dip.

Depth-Migrated Line
scale (1:1)

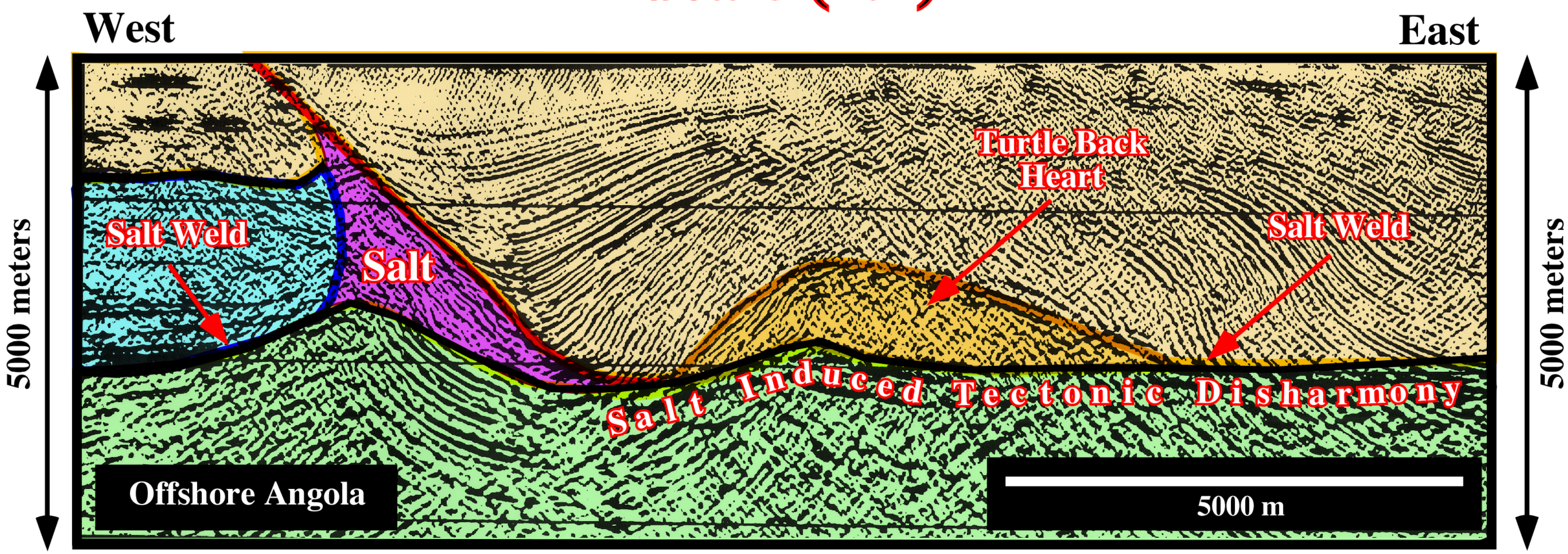

Fig. 64- This depth-migration version of the previous seismic line is at natural scale (1:1). Thus, theoretically, the dips of the reflectors correspond to the real dips of the bedding planes. Similarly, the dip of the listric fault plane is real. However, as you already probably noticed, this depth conversion is not perfect. The salt-induced tectonic disharmony should be more or less flat (dipping slightly seaward) and not undulated, as illustrated above. Actually, when this depth-migration conversion was performed, explorationists, due to raft-tectonics, did not properly control the velocity intervals in offshore Angola. Notice that due to halokinesis, in which tectonic inversions are frequent, the majority of the geometrical relationships (reflection terminations) are apparent. Indeed, as we will see later, the reflection terminations on the tectonic disharmony are not downlaps but tilted onlaps. In other words, the reflection terminations are not pristine, but deformed by salt flowage.

Depth-Migrated Line

vertical exageration x 2.5

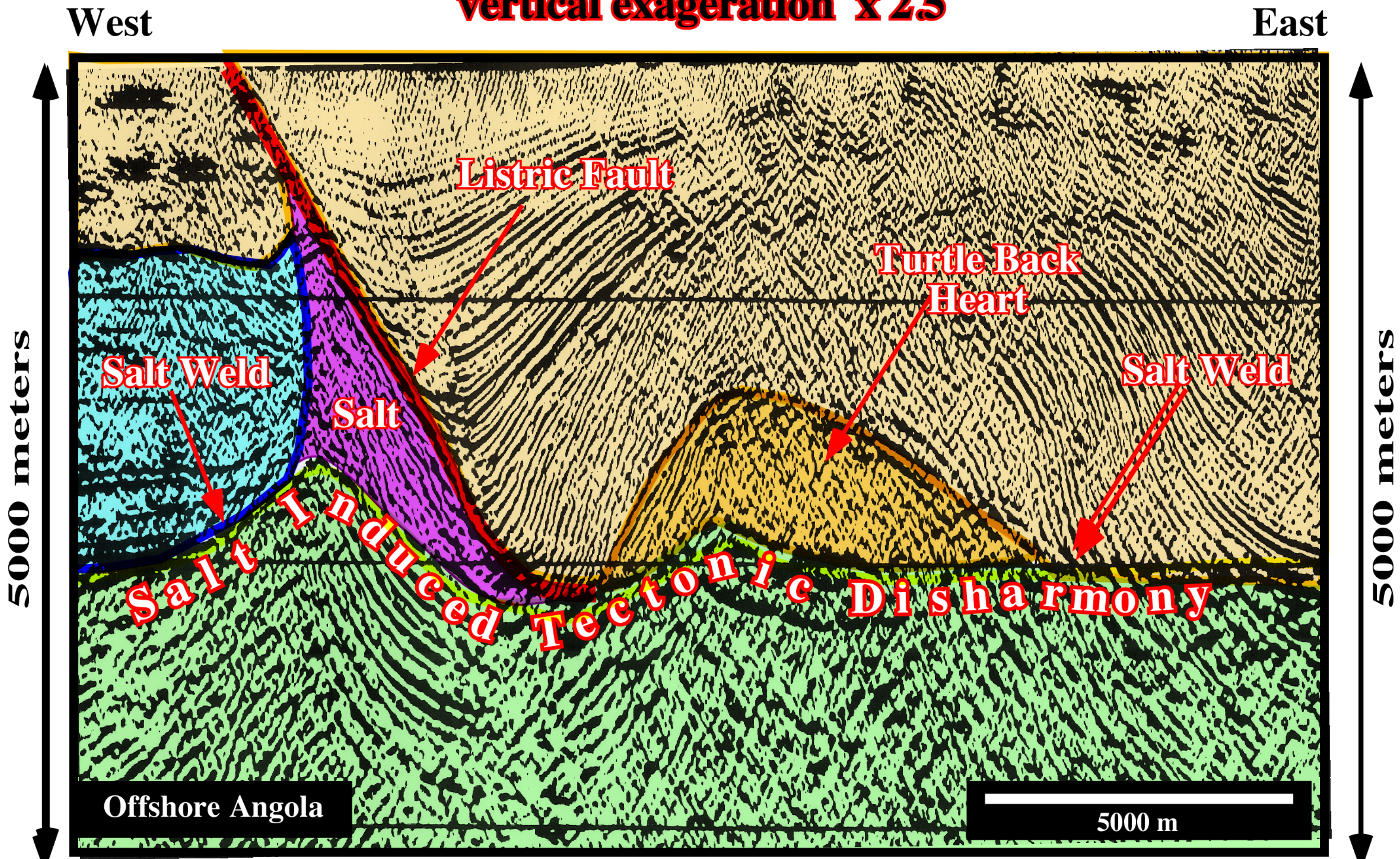

Fig. 65- The previous depth migrated line is here illustrated with a vertical exaggeration of 2.5 times. Explorationists and particularly those using workstations or PCs for interpretation of seismic data should never forget that Geology is scale dependent. Indeed, a progradation, for instance, can be interpreted as a continental slope or as deltaic slope (prodelta); it depends on vertical and horizontal scales. On the other hand, geological laws, as Goguel's law, Anderson's fault law, etc, can only be applied at natural scale data.

E.3) Lateral Arrivals

Another common difficulty encountered in the seismic interpretation is to be mislead by some organized energy not originated by reflectors included within the vertical plane defined by the profile, i.e. **lateral arrivals**. These conditions may defeat the interpreter if he attempts to interpret an isolated section. Each system of reflections may show sections of continuity, with areas of confusion between them. Without further evidence one cannot tell which continuous reflections are related to which others, nor can one tell the directions from which they arrive. Sometimes, the examination of other lines with better orientations, will reveal enough of the structure to enable one to interpret these complex sections with arrivals from various directions (**"side-swiper"**).

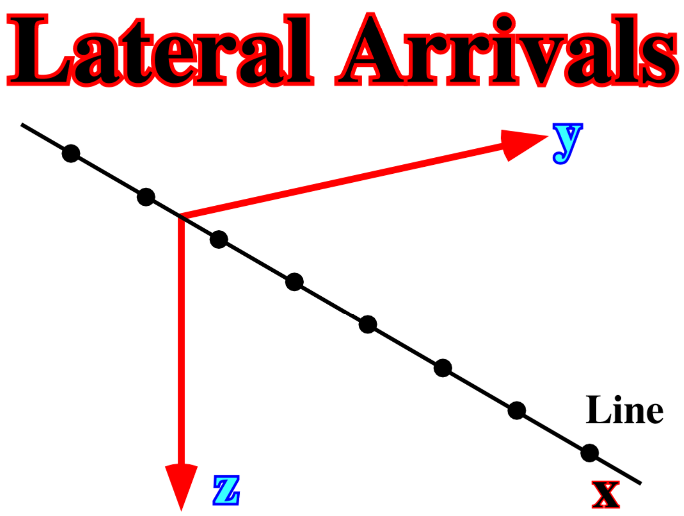

Fig. 66- Lateral arrivals are frequent in seismic lines, particularly in 2D data. They can indeed arrive from any direction as illustrated on this sketch.

One of the interpretation hazards that a seismic migration attempts to resolve by re-establishing true dips, is the one created by reflections generated off the plane of the section. **Dips are not always perpendicular** to the vertical plane determined by the field layout of the recording spread. If lateral dip component, relative to this plane, exists, some of the recorded events at least will be generated from areas that are off the vertical plane of the section. Only tri-dimensional seismic data, processed through 3D migration, can accurately place all reflections to their true location space.

Example:

The seismic line illustrated in fig. 67 shows a misleading well marked lateral arrival, which was initially interpreted by several explorationists as the trace of a reverse fault. They recognized two fault blocks with an important shortening on the up-thrown block and they associated the diachronic reflector with a fault plane. However, such an association is rarely observed. Indeed, generally, on a seismic line, fault planes are recognized by the associated seismic surfaces, that is to say, loci of reflections terminations and not by a reflector. However, several exceptions are well known:

(i) Fault planes intruded by volcanic or evaporitic material;

(ii) Well developed gouge zones ;

(iii) Strong impedance contrast between fault blocks,

(iv) Fault planes between sediments and basement, etc.

The same seismic profile was rebuilt using 3D data (random line, fig. 68). It clearly indicates there is any oblique diachronic reflector on the vertical plane defined by the profile. Such an absence corroborates the hypothesis that the oblique reflector, recognized on the 2D data, corresponds to a **lateral arrival**.

The essential difference between two-dimensional and three-dimensional migration may be illustrated with reference to a point reflector embedded in an homogeneous medium. On a seismic section, derived from a two-dimensional survey, the point reflector is imaged as a diffraction hyperbolae, and migration involves summing amplitudes along the hyperbolic curve and plotting the resultant event at the apex of hyperbolae.

The actual three-dimensional pattern associated with a point reflector is a **hyperbolic of rotation**. Diffraction hyperbola recorded in a two-dimensional survey represent a vertical slice through this hyperbolic. In a 3D survey, reflections are recorded from a surface area of the hyperbolic and three-dimensional migration involves summing amplitudes over the surface area defining the apex of the hyperbolic. A practical way of achieving this aim with crossed-array data, from a 3 dimensional land survey, **is the two-pass method**:

- First pass involves collapsing diffraction hyperbolas recorded in vertical sections along one of the orthogonal line directions.
- Series of local apexes, in these sections, together define a hyperbola in a vertical section along the perpendicular direction.
- Hyperbola can then be collapsed to define the apex of the hyperbolic.

Lateral Arrival

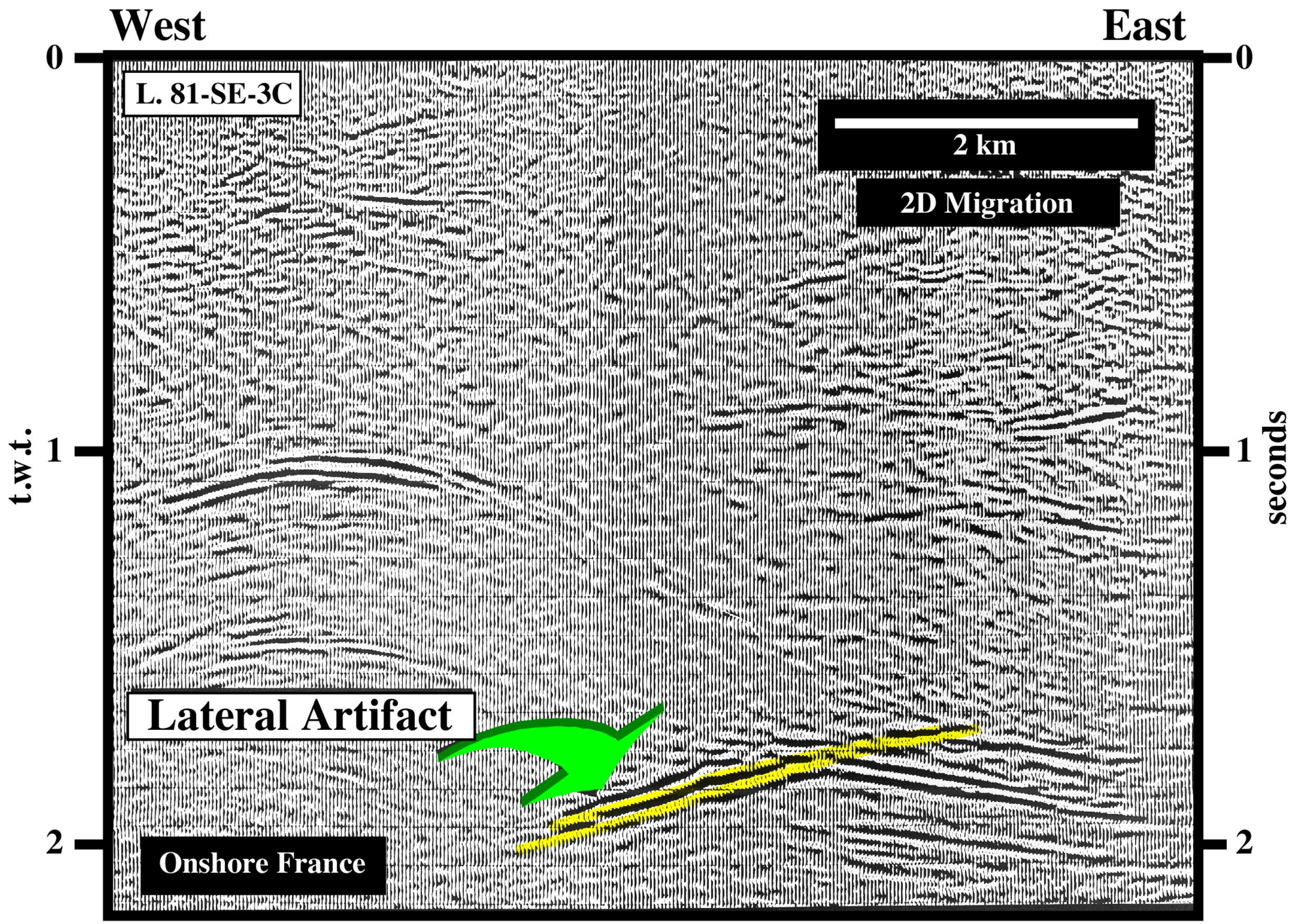

Fig. 67- The reflector (yellow) indicated by the green arrow was initially interpreted as a reverse fault plane. However, in spite of the fact that such interpretation is compatible with the regional geological setting, there is no logical reason (impedance contrast) to have a reflector underlying the fault plane. Actually, it seems to correspond to a lateral seismic artifact. The 3D data, illustrated on fig. 68, corroborates such a hypothesis.

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Switzerland

3D Data

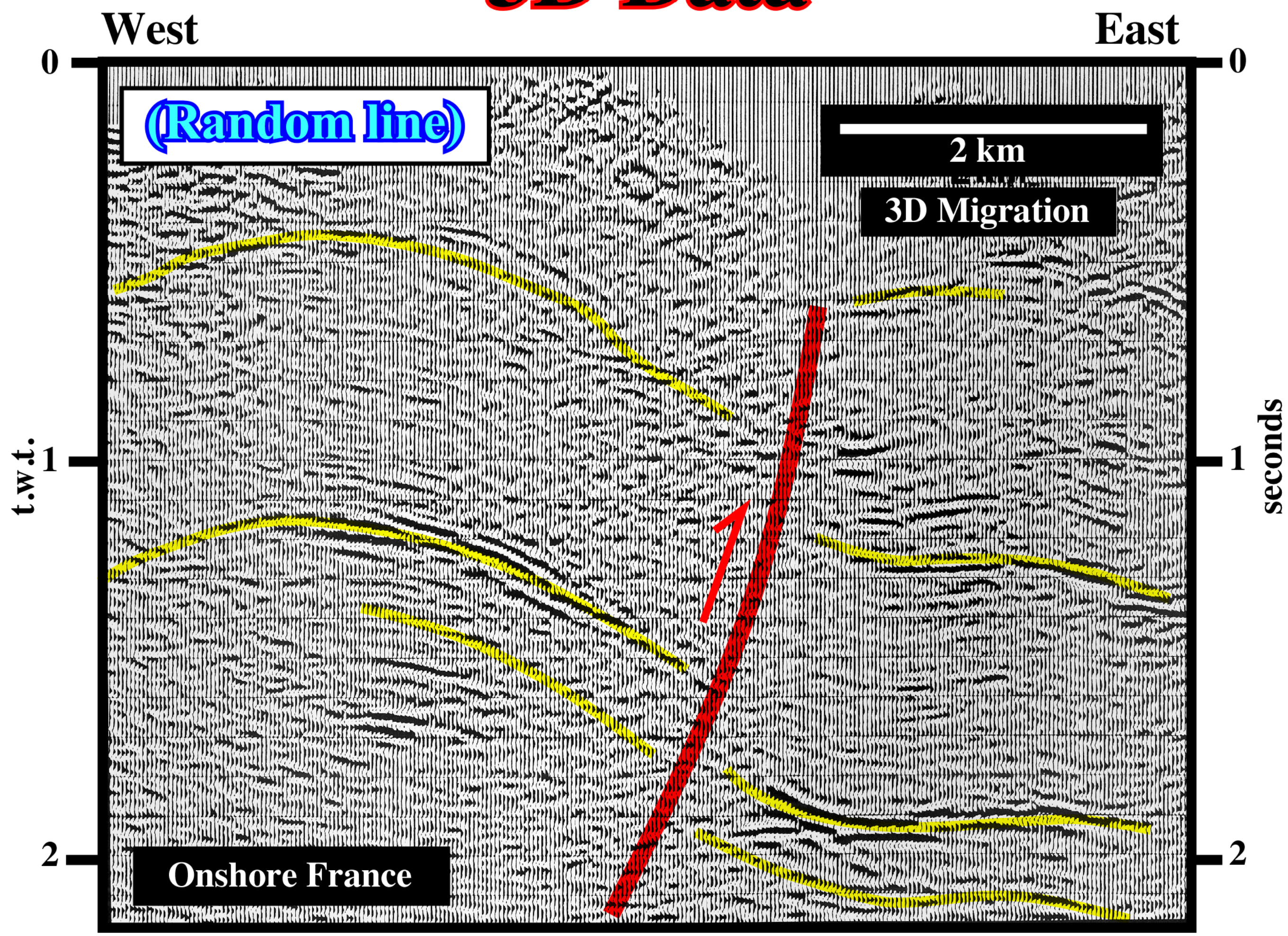


Fig. 68- The 3D random seismic line along the trace of the previous line corroborates the hypothesis that the oblique diachronic reflector on fig. 67 corresponds to a lateral arrival (sidewinder). Nevertheless, geologically speaking, this seismic line illustrates a faulted compressional structure, in which a reverse fault plane can be predicted by a seismic surface defined by reflection terminations.

So far, we have examined velocity anomalies and dip related distortions. In either case, recorded events, though displaced from their true position, image somehow a reflecting horizon and have therefore geological significance. Now, we will consider a different set of seismic events, which, though recorded as data, bear no relationship whatsoever to geology.

E. 4) Multiples

Actually, in addition to rays that return to the surface after reflection at single interface, known as primary reflection, there are many paths in a layered subsurface by which rays may return to the surface after reflection at more than one interface (fig. 69). Such rays are called: **multiple reflections** or **simply multiples**. These events must be eliminated from the recorded section in order to allow a better understanding of the geology of the area.

Different Energy Paths

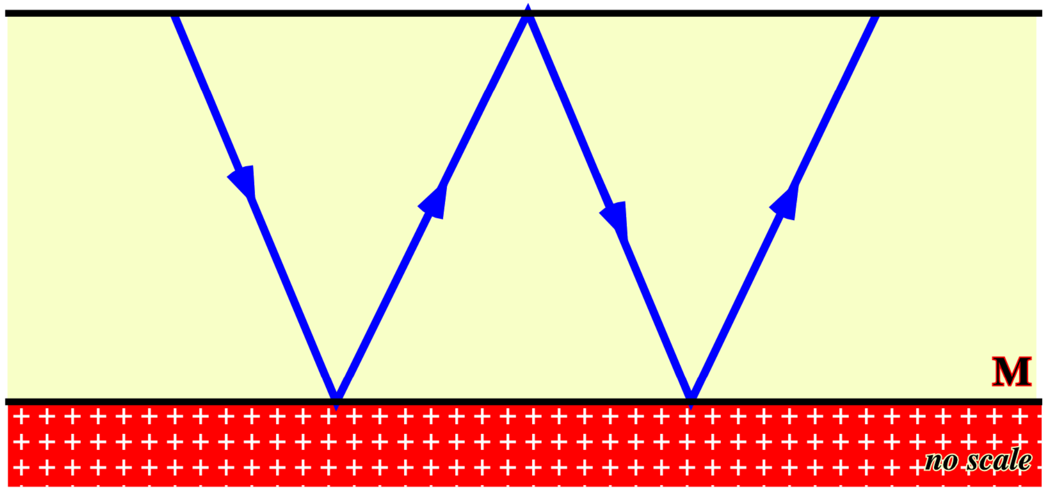


Fig. 69- The primary reflection from the marker M (the first rebound to the left) may be followed by a second arrival. This would be generated by the downward bounce of the residual energy on the upper interface and by its reflection on M.

Multiples are the principal set of spurious events interfering with seismic data (fig. 70):

- Their presence on a recorded section is due to the fact that an acoustic impedance contrast between two adjacent layers, reflects down-going wavesup as well as down.

A certain amount of seismic energy, therefore, is not transmitted from one layer to the next through the stratigraphic series along a simple two-way path. It remains trapped within a given formation producing an arrival on the recorded section at each rebound:

(i) **Surface multiples** (generated by the downward rebound at the air-ground interface) are the most common.

- They may be readily distinguished from primaries.

- They appear on the seismic section at **double** the time of primary reflections.

(ii) Generally, a multiple has **weaker amplitude** than its primary as most of the reflected energy is in fact transmitted through.

- However, this is not always the case. If the acoustic impedance contrasts generating multiples are higher than the contrasts generating primary reflectors, for a given time, the spurious events will be stronger on the seismic section.

(iii) Other situations may also occur, such as **resonance** within a layer or fortuitous summing of a multiple with later primary arrivals within the same frequency range.

The travel path of **internal multiples**, generated anywhere within the stratigraphic sequence by the trapping of energy within a layer or a combination of layers, is much more difficult to reconstruct.

In **water layer reverberations**, as sketched in fig. 71, the rays from a marine source are repeatedly reflected at the seabed and sea surface (**ringing in water**). This type of multiple (also visible on previous figure), is possibly the most annoying but, fortunately, it is the easiest to eliminate.

Multiples

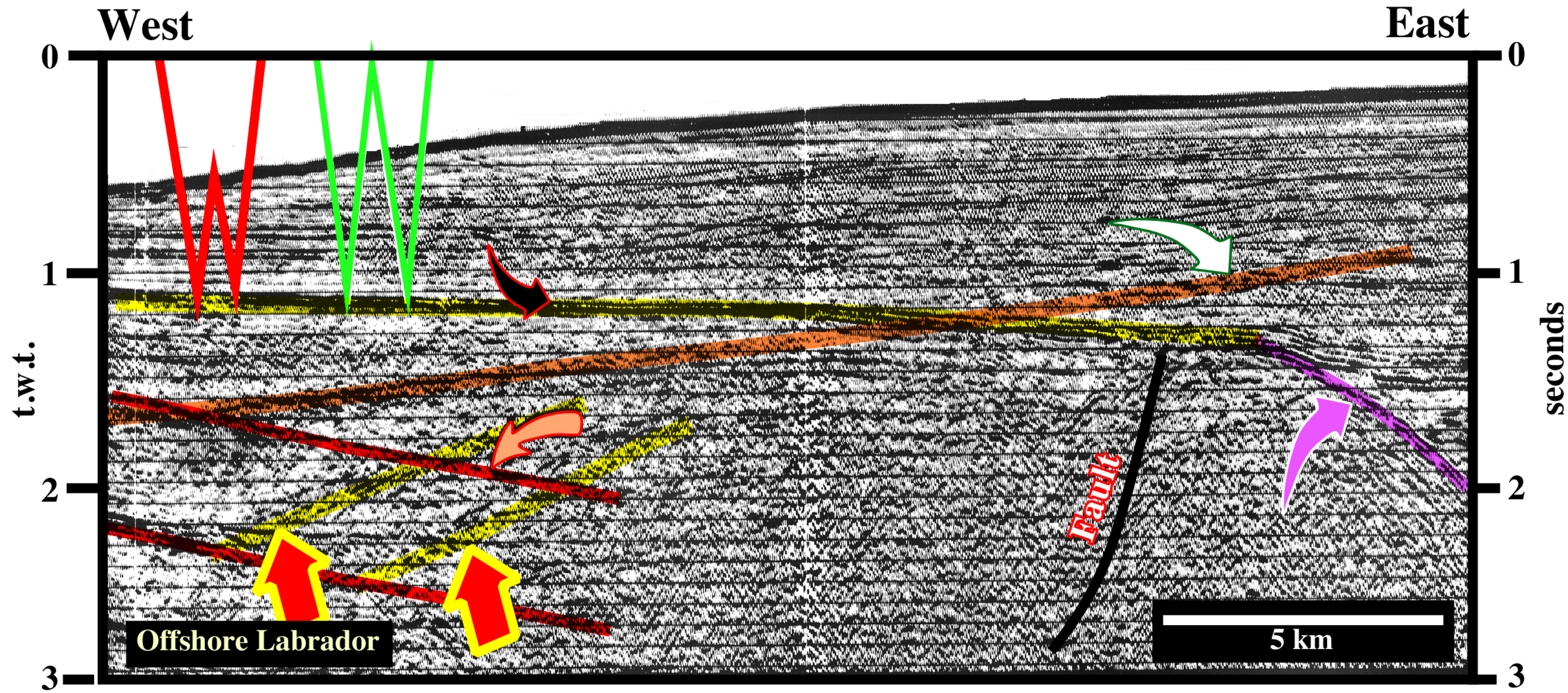


Fig. 70- This old seismic line comes from offshore Labrador (an Atlantic-type divergent margin), which locally overlies late Cretaceous rift-type basins. Admittedly, this line is affected by numerous multiples. Most of them have higher amplitude than their corresponding primaries. Three successive rebounds within the water layer, if not more, are visible and can be readily accounted for. Several other multiples however appear to be generated by the strong dipping horizon at 1 second to the left of the section. These are possibly secondary rebounds of this primary event: (i) within the water layer, (ii) downward on the water bottom or (iii) a combination of both.

The two interfaces, at either side of the water level, are excellent reflectors.

- **The air-water acoustic impedance contrast is as effective as the water-sediment contrast.**
- **Hence, bound by two strong reflecting interfaces, the water layer is an excellent multiple-generating medium. This is particularly so, on hard water-bottom areas where sediments are compacted and well consolidated.**

In the example shown below, repeated travel paths, within the water layer, are summed to the travel time to the indicated deeper horizon. Each rebound generates successive multiples of this horizon.

Reverberation

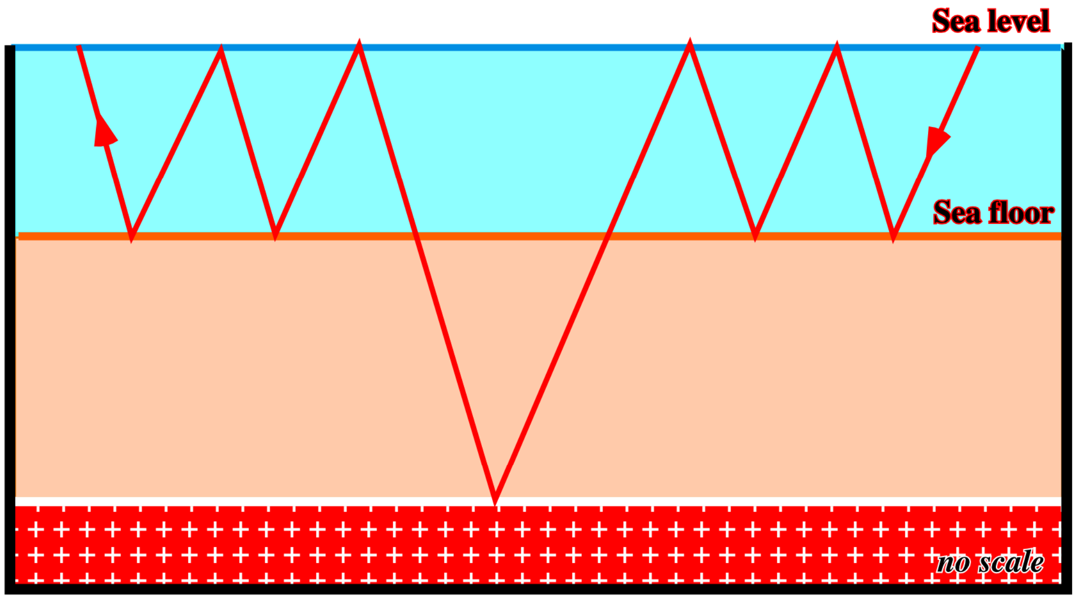


Fig. 71- Reverberation or ringing in water is illustrated on this sketch. Reverberation is also known as singing, that is to say, seismic resonance produced by short-path multiples in a water layer. Indeed, as said previously, repeated travel paths within the water layer are summed to the travel time to the indicated deeper horizon.

The marine section illustrated on fig. 72, from offshore Labrador, shows this kind of multiple. In this particular example:

- The multiple reflections have amplitudes comparable with the primary reflections.

- The strong amplitude is due to the high reflection coefficient of the interfaces.

Ringing

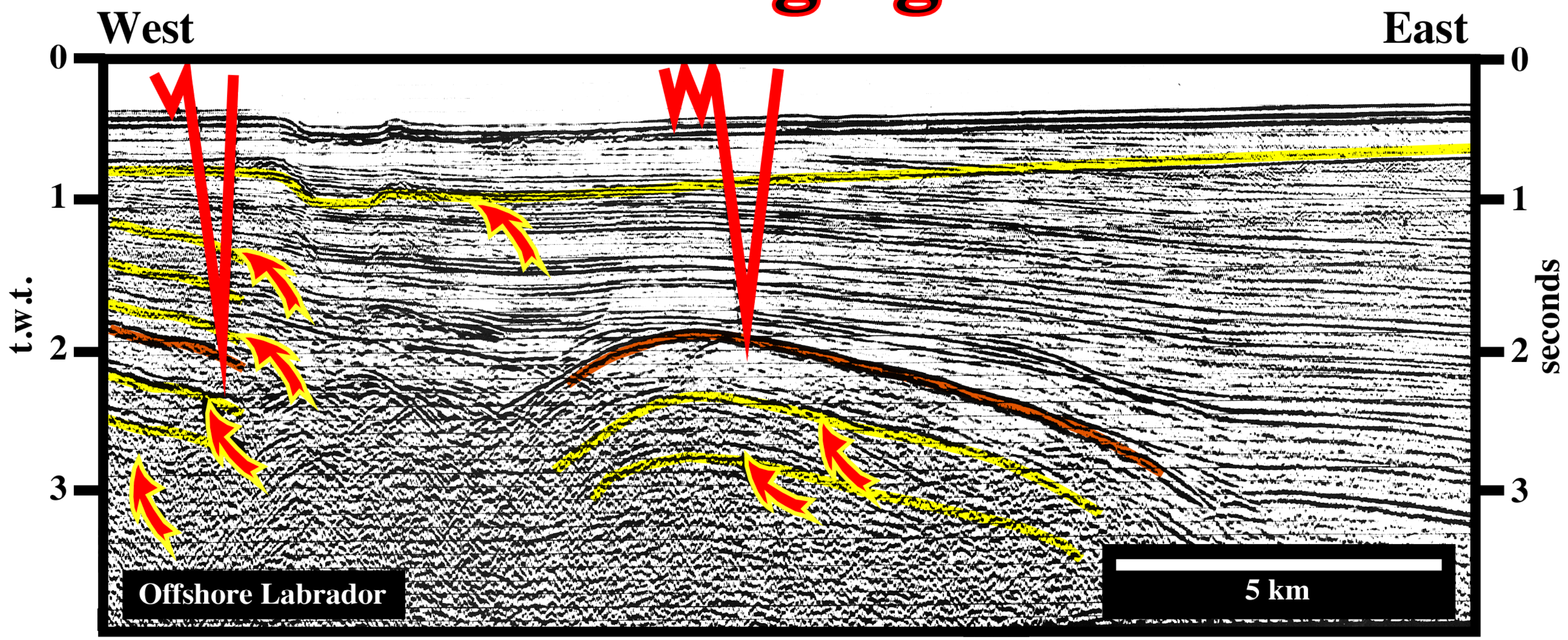


Fig. 72- This marine section from offshore Labrador shows several multiples induced by the sea level. A strong reflection, culminating at approximately 2 seconds, is visible in the middle of the section. Because of the high acoustic impedance contrast at the water-bottom, 1st and 2nd order multiples are produced within the water layer (ringing / reverberations). The time difference between the primary and its first multiple is, every where, equal to the time through the water layer.

The sketch illustrated on fig. 73 attempts to schematize the most probable path, between shot point and receiver, that an acoustic wave travelling through the sedimentary intervals, may chose. Direct primary arrivals and different sets of multiples are indicated.

Different Energy Paths

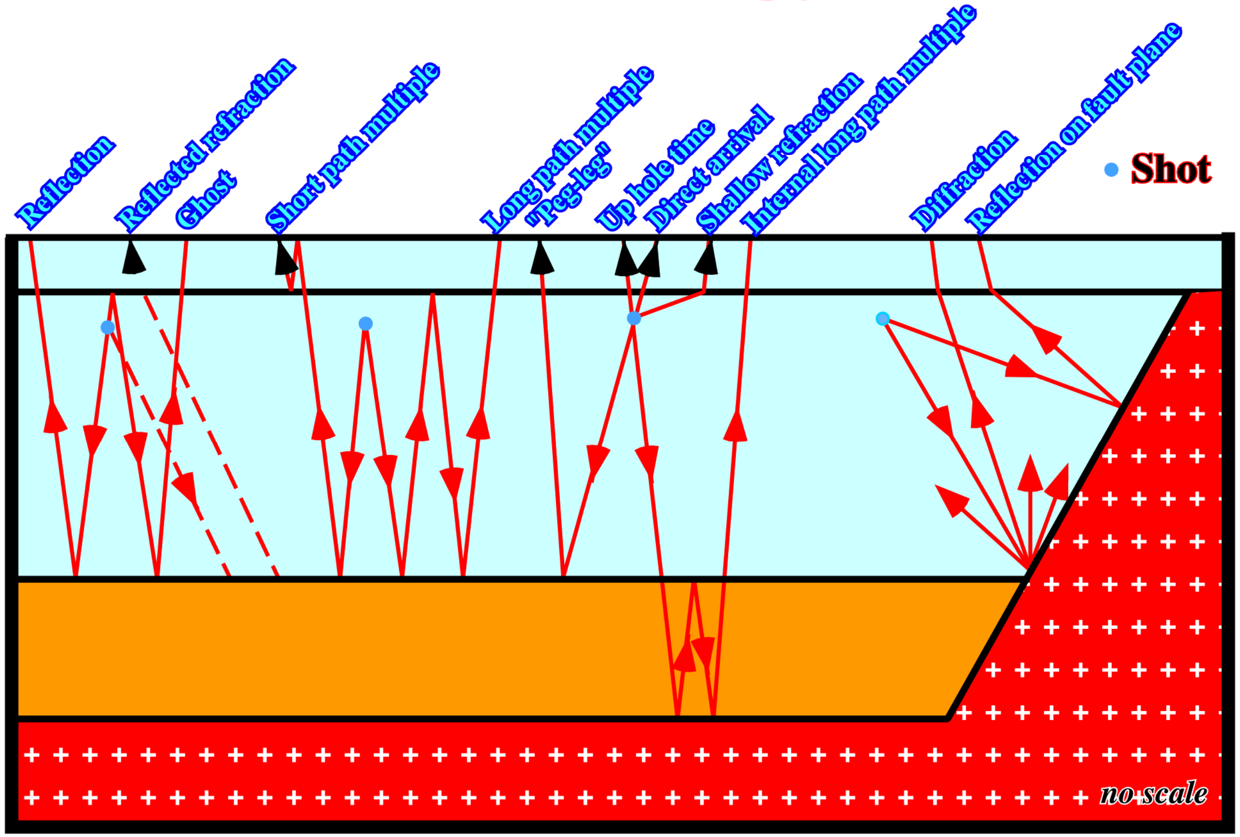


Fig. 73- On this sketch, in which the shots are underground, below the base of weathered layer, from left to right, are depicted:(i) Reflection, (ii) Reflection refraction, (iii) Ghost, (iv) Short path multiple, (v) Long path multiple, (vi) Peg leg, (vii) Up hole time, (viii) Direct arrival, (ix) Shallow refraction, (x) Internal long path multiple, (xi) Diffraction, (xii) Reflection on fault plane.

The more frequent multiples, i.e. reflection events having suffered more than one reflection, illustrated on fig. 73, are:

- **Diffraction**,

  It is a radial scattering of incident seismic energy.

- **Reflected refraction**,

  A refraction along a bedding plane or unconformity (reflectors) with appropriate velocity contrast that is reflected back from steep surfaces. Reflected refractions contain information only about the refractor.

- **Ghost**,

  It is a reflection event arriving a short time after the primary from the surface or the base of weathered layer (buried explosion on land).

- **Short path multiple**,

  It is a multiple-reflection involving only a short additional path length arriving very soon after the primary event.

- **Long path multiple**,

  It is a multiple-reflection involving additional path length sufficiently long that it is a distinct and separate event in the seismic record.

- **"Peg leg"**,

  It is a multiple-reflection induced by a ringing between two reflectors.

5.5) Diffractions

At abrupt discontinuities in interfaces, or structures whose radius of curvature is shorter than the wavelength of incident waves, the law of reflection and refraction no longer apply. Such phenomena give rise to a radial scattering of incident seismic energy known as **diffractions**. Properly speaking, they are considered as noise but they could help to interpret discontinuities on un-migrated data. A hyperbolic pattern, on a non-migrated times ection , however, may be of use to the interpreter as it points out the existence of subsurface discontinuities. The front of all incident waves, propagating through a homogeneous, isotropic medium obey the principle defined by Huygens: (i) whether on a plane or an uneven disturbed surface, or as an isolated point mass, points struck by an incident wave behave as new emission sources and radiate energy in all directions on a spherical front (fig. 74); (ii) for a continuous surface, most of the energy so emitted by adjacent points, actually cancels out; (iii) the reflected ray path reaches the receiver, in most cases, as a first arrival.

Diffractions

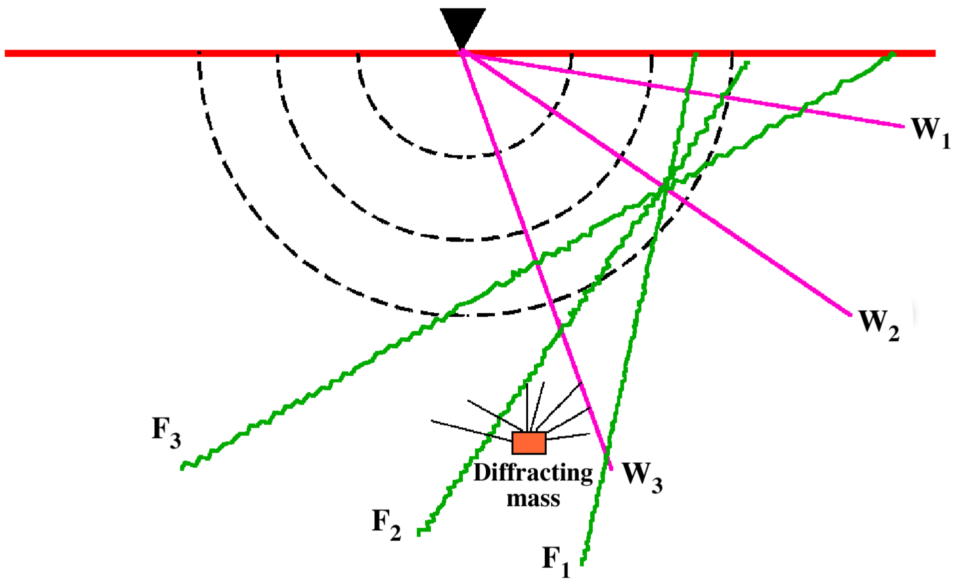


Fig. 74- Diffractions principles

A diffraction from a given subsurface point persists when the wave length of the striking energy is greater than the longest dimension referred to underground object and cancellation from other lateral sources cannot occur. Generally speaking, a diffraction is produced by the incidence of a wave front acoustic impedance discontinuity of limited extent at the scale of the section, which could be assimilated to a point mass:

- This could be either an isolated speck in space, or the intersection of a linear event (dike, the apex of a high angle fold, a fault plane, etc.) with the plane of the section.
- Diffractions may also arise from the intersection, of two apparently separated markers.
- This is often the case when reflection from the up-thrown and the down-thrown fault blocks bounces off the plane of a fault.

Diffractions

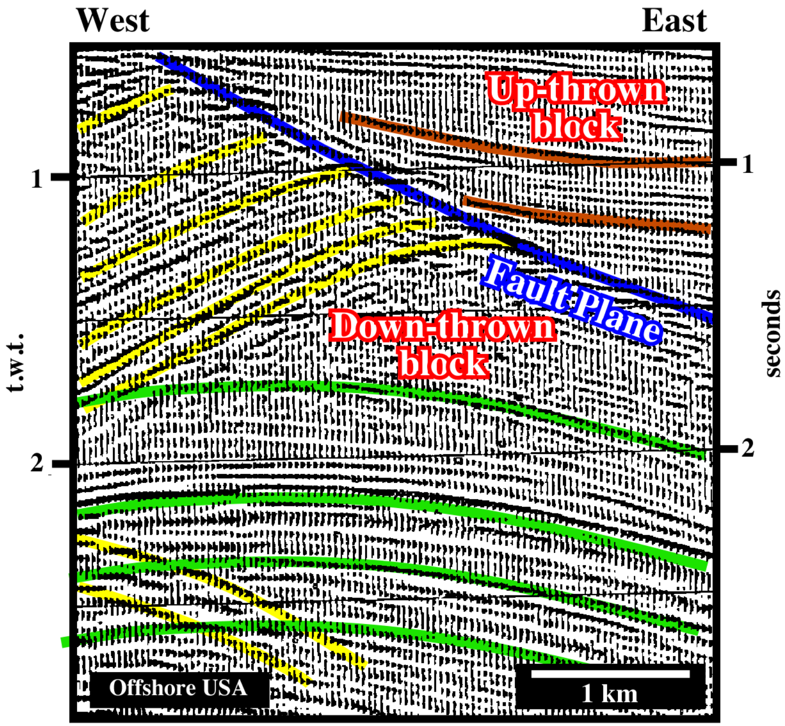


Fig. 75- This non-migrated seismic section shows a great number of diffraction patterns pointing to the existence of a discontinuity between two fault blocks. On the left block, it should be noticed that diffraction amplitudes are greater that reflection amplitudes. On the lower left corner, the right leg of a diffraction is probably originated from a point located off the plane of the section.

Parasites

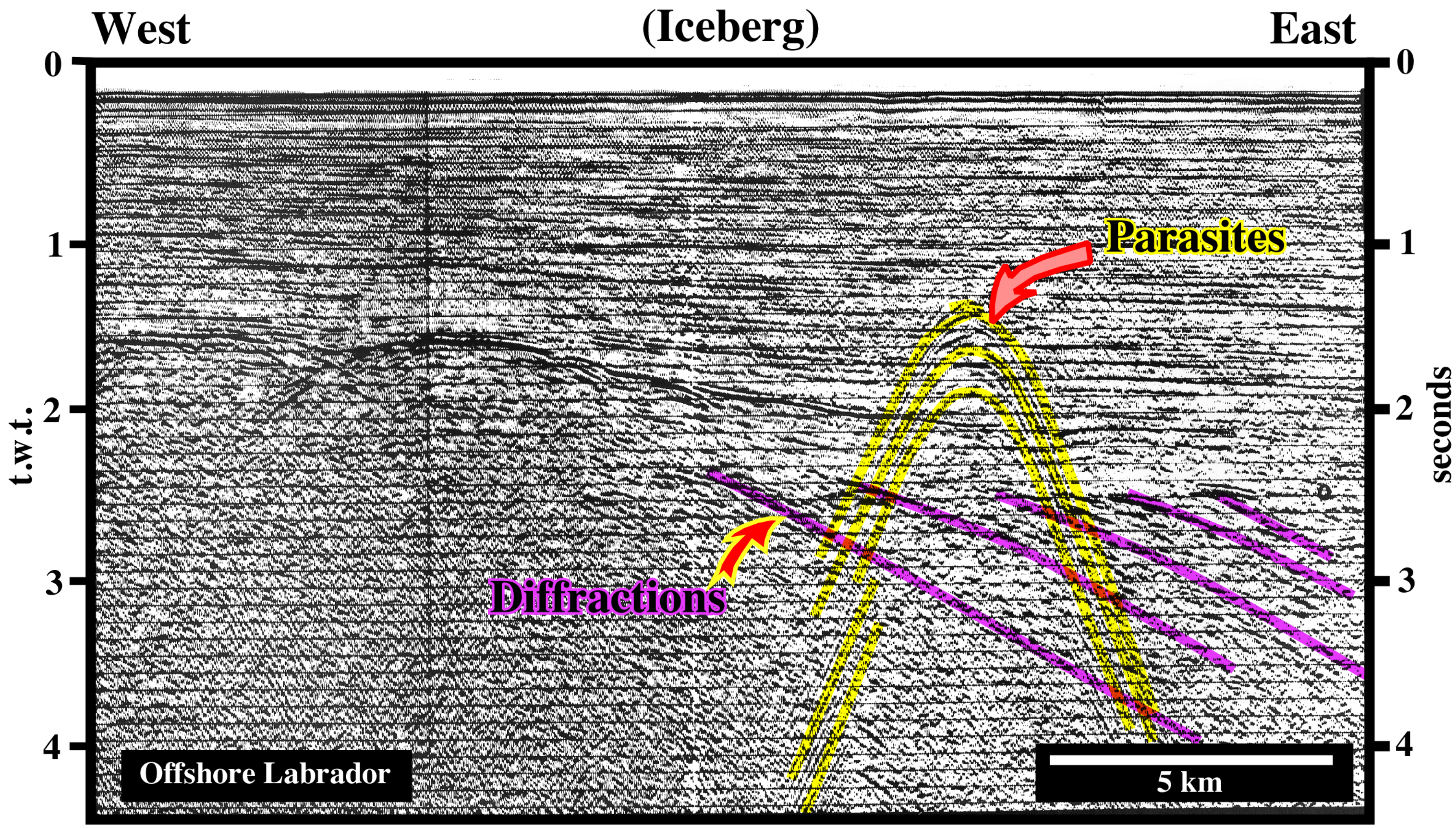


Fig. 76 - On this un-migrated seismic line from Labrador Sea (Atlantic-type margin overlying rift-type basins) parasites (in yellow), induced by an iceberg, are quite evident. Indeed, at the time of shooting, an iceberg was located no more than 1000 meters from the seismic vessel. Diffractions associated with the top of the basement (Precambrian supracrustal rocks) are also quite visible. Notice that, on the migrated version of this line, the downward hyperbolic geometry of the parasites chances into an upward hyperbolic geometry.

Diffraction may originate in the subsurface from the edges of fault blocks (fig.75), or they may come from sources much closer to the surface. In marine seismic for instance, floating objects, such as ships, icebergs or wrecks on the ocean floor, often produce diffractions (fig. 76). As long as diffractions are originated from objects within the plane of the seismic section, migration (when the correct velocities are used) **collapses all the energy** and **focuses the hyperbola** on a single point at its apex. Hence, diffractions are only **visible on seismic data prior to migration**. Non migrated sections may then be useful to locate local discontinuities. Common sources of diffraction in the ground include edges of faulted layers and small isolated objects, such as boulders, icebergs, etc. On fig. 77, the more frequent origins of hyperbolae that one can find on un-migrated seismic lines are summarized. Generally, they can be created by: (i) **Folds** (when the axial plane is vertical, the hyperbolae do not show polarity change; the curvature must be compared to the NMO hyperbolae at the same depth), (ii) **Faults** and **Flexures**.

Hyperbolae Origin

A NO POLARITY CHANGE	Anticline Syncline Fault ?	
1) CURVATURE > NMO AT SAME LEVEL	Sharp Syncline Fault } NORMAL TO LINE	
2) CURVATURE = NMO AT SAME LEVEL	Syncline Fault Fold } SLANT TO LINE	
3) CURVATURE < NMO AT SAME LEVEL	Anticline Syncline-Fault	
B POLARITY CHANGE	Fault Fold	
C APEX FALL ALONG A SINGLE LINE	Anticline Syncline Fault	
D APEX FALL ALONG TWO LINE	Flexure	

Fig. 77- This table gives some of the criteria useful to interpret hyperbolic patterns on an un-migrated section. The elements considered here are the polarity (as it changes from one leg of the conic to the other) and the curvature as compared to the NMO (normal move-out) hyperbola at the same depth.

It must be noticed that the criteria illustrated on fig. 78 are not sufficiently discriminatory. Simpler criteria do exist to distinguish a syncline from an anticline and a fault from a fold, as illustrated on fig. 79. In order to examine the seismic image of a fault, we will consider the geological model illustrated on fig. 79, where:

(i) The fault plane is vertical (local geological situation).

(ii) The up-thrown and down-thrown fault blocks have the same dip.

(iii) A seismic profile (line C) intercepts the fault plane with an angle α.

Faults & Flexures

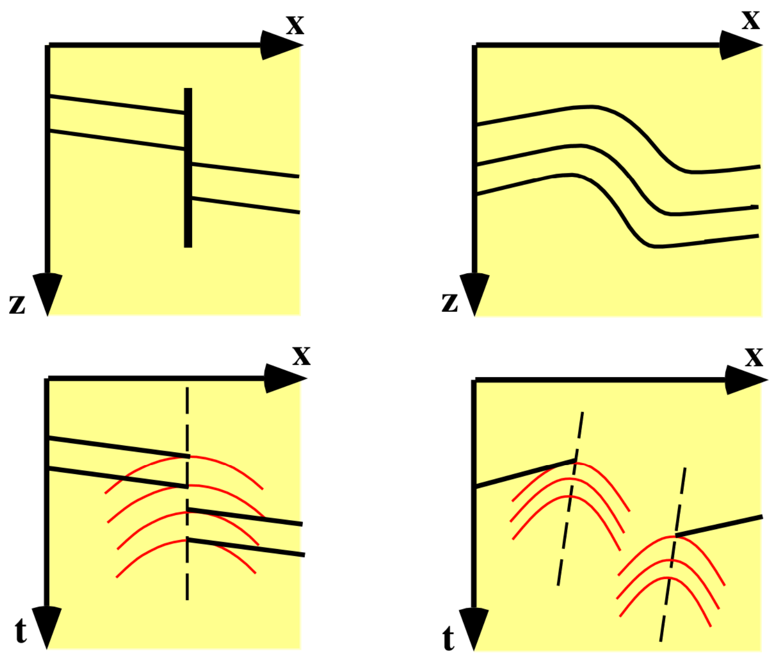
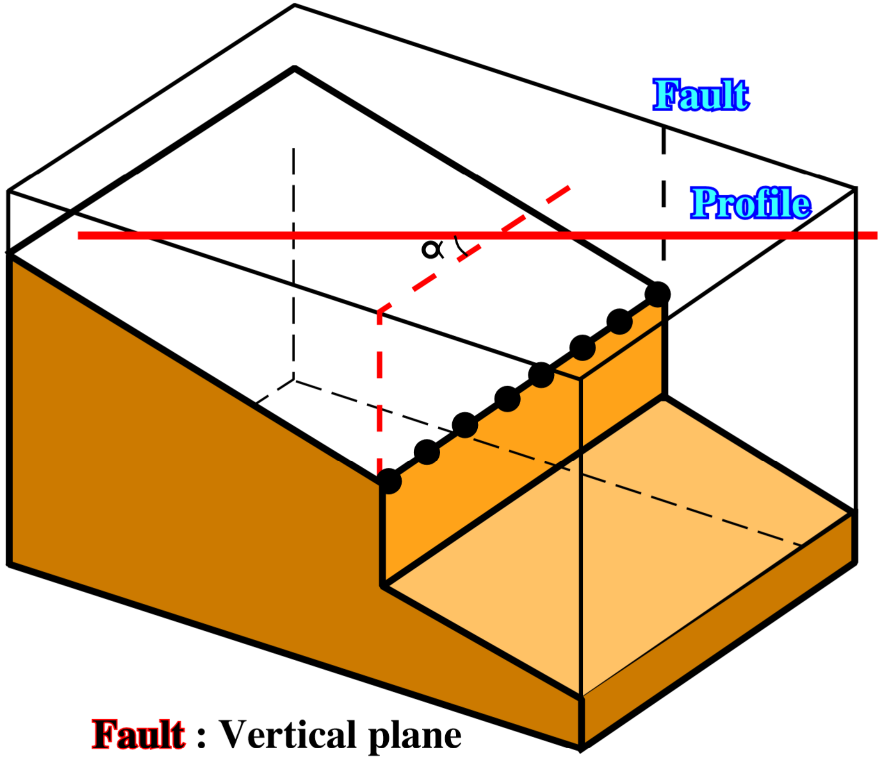


Fig. 1.78- The presence of superposed hyperbolas on a seismic line may assist in correctly interpreting a fault or a flexure. In the case of a fault (on the left), hyperbolae line up vertically over the intersection of the fault plane with the plane of the section. In the case of a flexure, two sets of displaced hyperbolas pinpoint the top and the base on the flexure. However, interpreters must not forget that vertical normal faults do not exist in Geology. Only very locally, the geometry of a normal fault plane is vertical. Indeed, the aim of a normal fault is to lengthen the sediments. Hence by definition, the dip of a normal fault must increase with depth, that is to say its hade (angle with the vertical measured perpendicular to strike) must increase, in order to length the sediments. In addition, as the compressional wave velocity of the sediments increase with depth, and seismic lines are time-profiles, in a seismic line all fault planes must flatten in depth.

Block Diagram



Fault : Vertical plane
High & low compartments : Dipping planes

Fig. 79- This block diagram illustrates the geological model used to study the seismic image of a normal fault. Spite the impossibility to develop large-scale vertical normal fault planes for simplicity, we assume a local vertical fault plane geometry. Notice that in this model the fault blocks have the same dip.

The time response of such a model is depicted on fig. 80:

A) On the upper part of the figure:

- "BC" is the trace of the seismic line on the ground surface.
- "F" is the trace of the vertical fault plane on the ground surface.
- "α" is the intersection angle between the fault plane and the seismic line.

Time Response

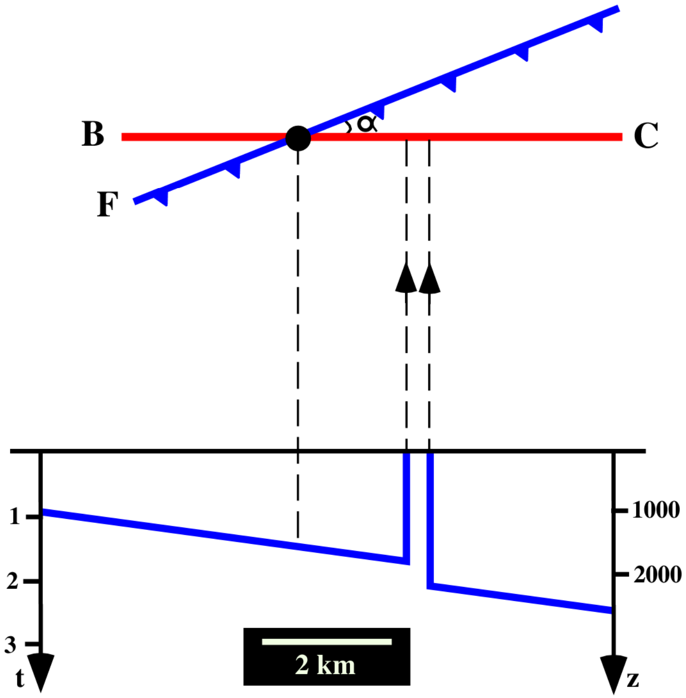


Fig. 80- The time answer of the previous faulting geological model is depicted on the lower part of this sketch. On top, the traces of the seismic line and the vertical fault plane are represented. Note that the location of the fault is displaced down-dip. In addition, it corresponds to a blind zone rather than a vertical reflection.

B) On the lower part, the time response of this simple model it is illustrated:

(i) The fault is **not located right under the corresponding shot point** on the surface.

(ii) It is slightly displayed to the right of it (down-dip).

(iii) The fault is not imaged as a vertical reflection segment but as a **blind zone** separating the two blocks.

Similarly to what we have already seen, in the case of migration with dipping beds, the shortest travel times (the travelling paths perpendicular to the marker) are not to reflection points situated on the vertical plane of the section, but to points up-dip of it. The depth-section response on a vertical plane is shown on fig. 81.

Depth Response

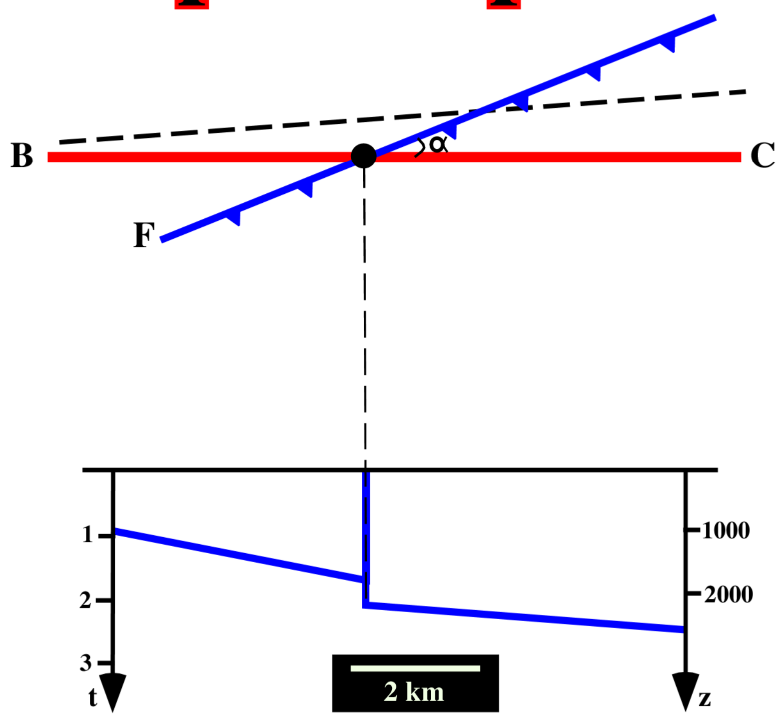


Fig. 81- The lower part of this sketch shows the theoretical vertical depth-section corresponding to the recorded section of the previous theoretical model. The upper part shows a plane view of the position of the actual reflection points of the marker as projected on the ground surface.

Let's see a seismic example of such a geological model (fig. 82).

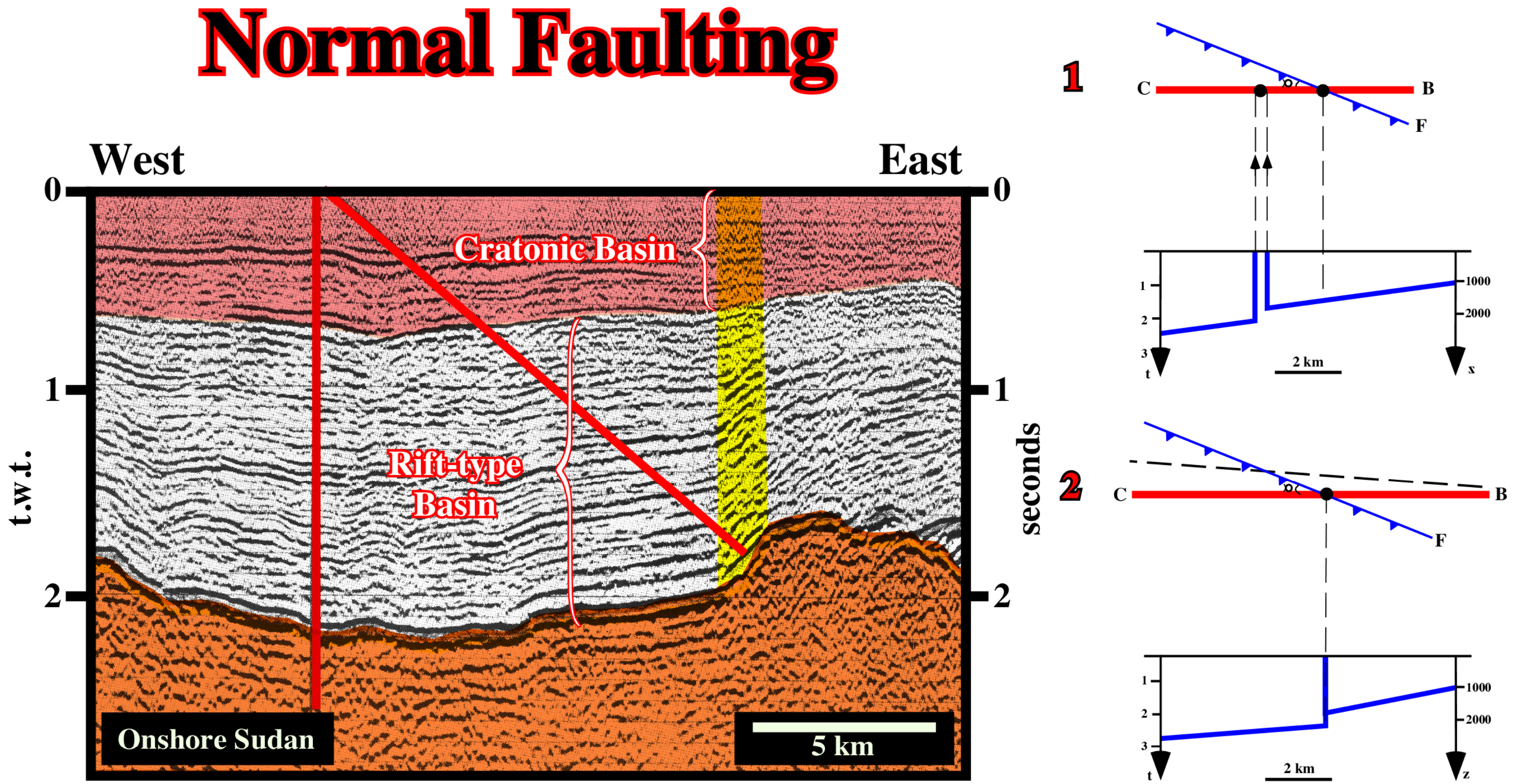


Fig. 82- On this line from onshore Sudan, that is to say, from a rift-type basin (Bally's basin classification) overlain by a quite thin cratonic basin, a blind zone (yellow) is developed between the up-thrown and down-thrown blocks of the normal fault. One can conclude that: (i) the seismic profile intersects the fault plane at certain angle, (ii) the true position of the fault, with respect to the profile, is to be found rightward of its apparent position on the time section.

The interpretation of the previous seismic line is justified as follows:

- The disturbed zone to the right could either be a vertical fault or a flexure.
- In fact, as illustrated on fig. 83, several vertically aligned hyperbolae are visible:

(i) Their curvature conform with the curvature of dynamic corrections (in overlay).
(ii) It is most likely that they are in fact diffraction images.
(iii) As only one set of superimposed hyperbolae is present (and not two), the pattern most probably indicates the presence of a fault and not a flexure on the seismic line.
(iv) The apparent velocity, as measured on the hyperbolic pattern, is higher than the NMO velocity at the corresponding depth. This would indicate the line is not perpendicular to the fault plane.

Superimposed Hyperbolas

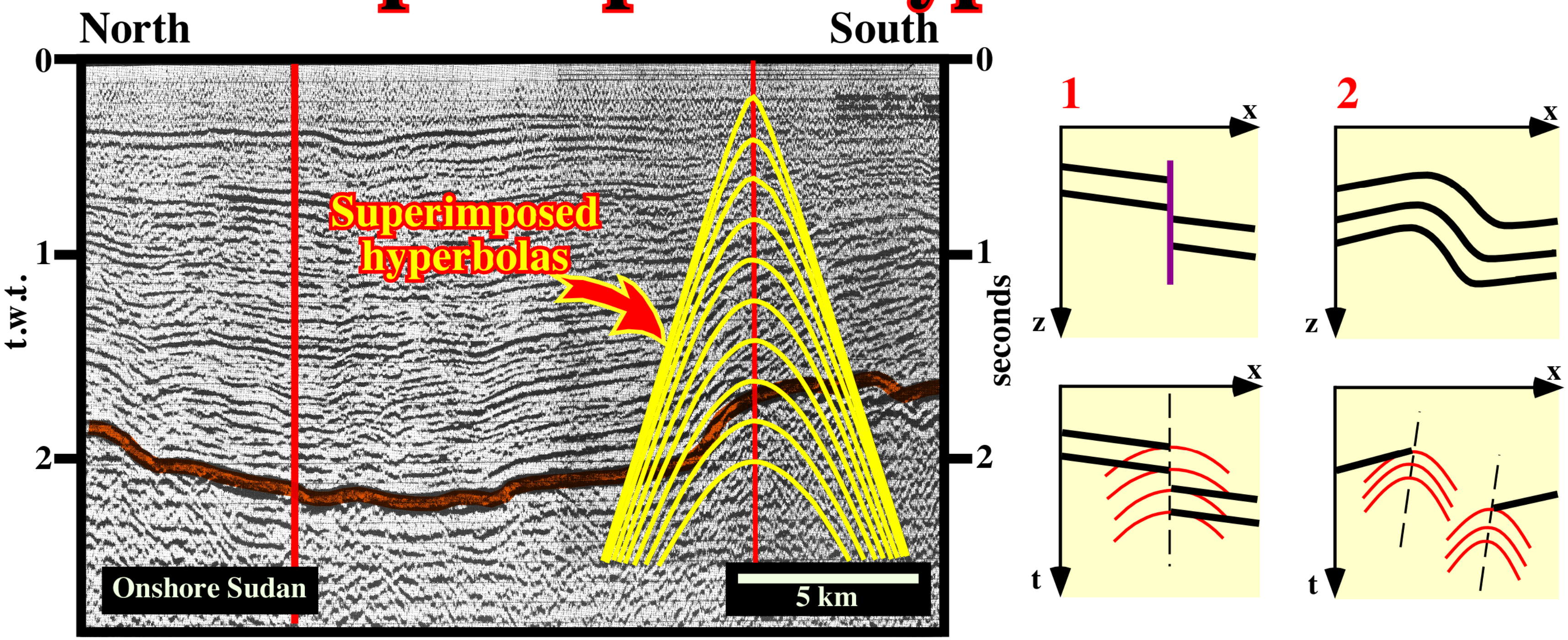


Fig. 83- As just one set of superimposed hyperbolas fits the diffraction recognized on the seismic line, the most likely meaning of such diffractions is the presence of a fault plane.

Before studying the next geological normal faulting model, it will be interesting to analyse the interpretation consequences of the obliquity of seismic profiles in vertical normal fault planes (fig. 84).

Interpretation Sketch

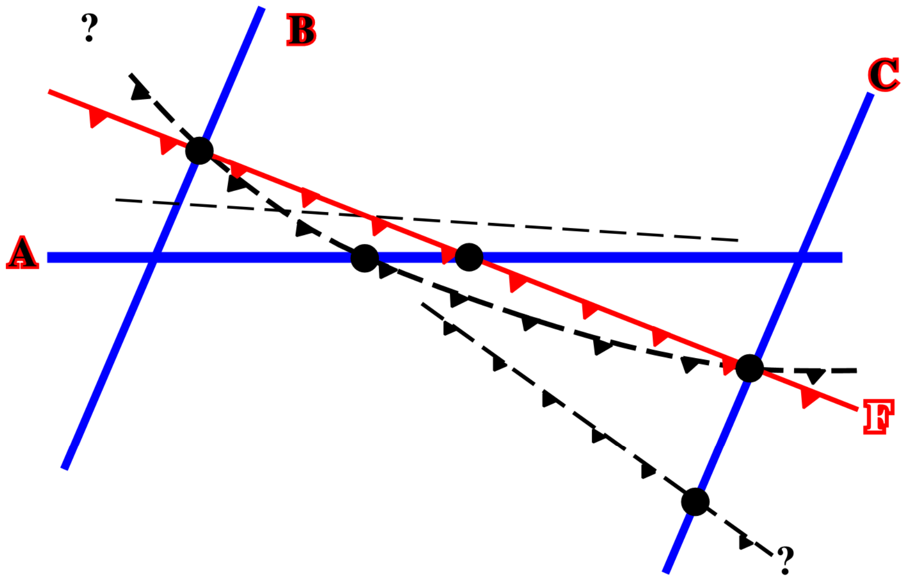


Fig. 84- This sketch tackles a common problem in seismic interpretation. The plane view shows, in red, the projection on the ground surface of a fault plane "F", and in blue, is indicated the location of three distinct seismic profiles. One is oblique to the fault, the others are perpendicular to it in the direction of the dip.

The black lines indicate the possible interpretations of the fault on the basis of the recorded data (black dots):

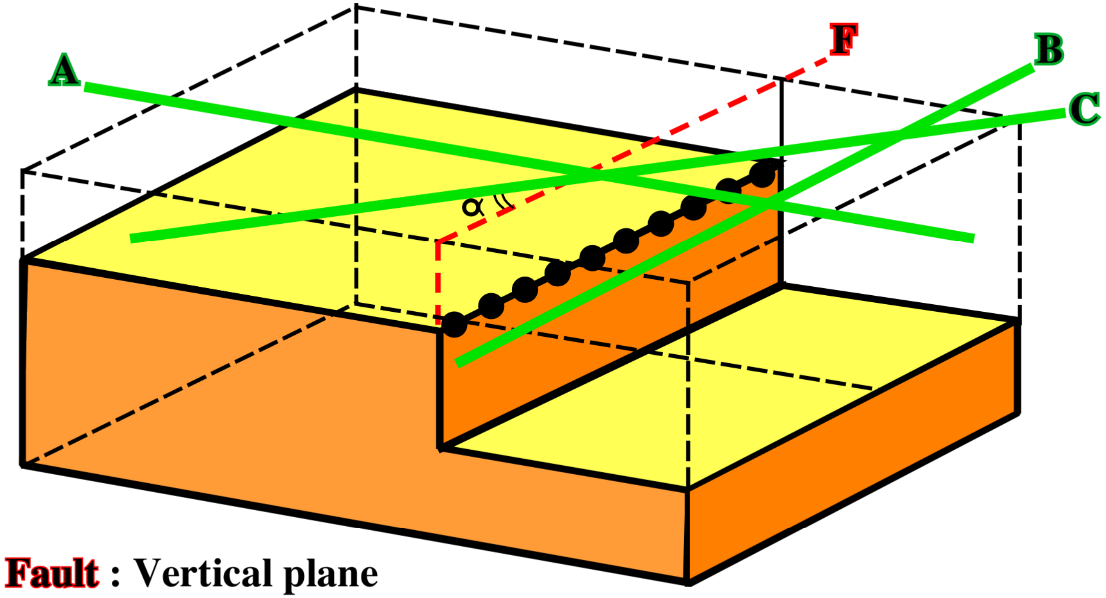
- Lines "B" and "C" correctly place the fault at its true position.
- On the other hand, "A", for the reasons we have examined, displaces the fault up-dip along the line of a distance that depends on the angle of inclination of the reflecting bed.
- If a second fault exists in the area, and is recorded further down on "C", the interpreter would naturally tend to draw a straight line joining the fault indications as recorded on the three profiles.
- The correct correlation however is the curved line shown in the figure.

If the bed is dipping, all three lines will displace the fault. Lines B and C will migrate the fault to its true position, but A will not because the reflecting points are off the plane of the section.

The next geological normal faulted model illustrated on fig. 85 is characterized by:

(i) A vertical fault plane (local geological situation).
(ii) Horizontal bedding planes and
(iii) Three seismic profiles (one is oblique to the strike of the fault, the others perpendicular).

Block Diagram



Fault : Vertical plane
High & low compartments : Horizontal planes

Fig. 85- This block diagram illustrates a geological model in which a normal faulting displacing horizontal faulted blocks is crossed by three seismic lines. One of the lines is perpendicular to the fault plane, while the others are oblique.

The time and depth-seismic responses of this simple geological model are illustrated on fig. 86. The top figures are the actual depth cross-sections. Below, the three corresponding time sections are represented.

Profile "A" (perpendicular to the fault plane):

- The position of the fault is the same on the depth and on time sections.
- The apparent velocity corresponding to the hyperbolic diffraction patterns is the same as the average velocity through the formation.

Depth & Time Models

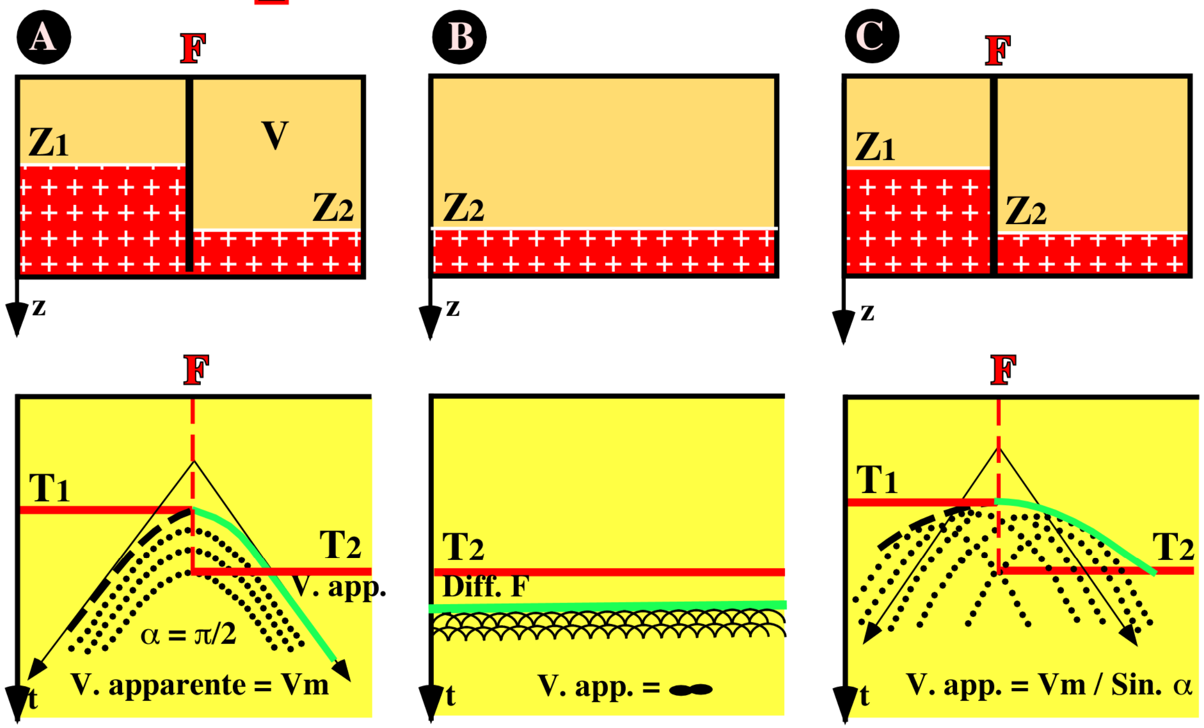


Fig. 86- Here are illustrated the depth and time responses along the seismic profiles A, B, C of the geological model depicted on fig. 85.

Profile “B” (parallel to the fault):

- The reflections from the surface of the down-thrown block and from the edge of the up-thrown block are both horizontal and visible.
- They are accompanied by a diffraction pattern whose envelope is displaced relative to the edge of the fault.

Profile “C” (oblique to the fault plane):

- Since the assumed model has 0 dip, the time image of this plane corresponds to its true depth position even though the seismic profile is slanted with respect to the fault plane.
- The apparent velocities, however, as determined by the diffraction hyperbolae, deformed by the skew of the line, are then the average velocity within the formation.

In order to avoid misleading interpretations in which diffractions are taken as geological events, we will list the diffractions characteristics generated at the end of a layer and at the end of a faulted layer (fig. 87 and 88):

- The polarity of the hyperbola legs, outward from the slab, has the same polarity as the reflection from the slab.
- The polarity of the hyperbola legs, beneath the slab, is opposite to the polarity of the reflection from the slab.
- The amplitude of the diffraction hyperbola is half the absolute value of the amplitude of the reflection from the truncated layer.
- A horizontal reflecting truncated layer is tangent to the diffraction hyperbola at its apex.
- A dipping reflecting truncated layer intercepts the hyperbola down from the apex of the conic.
- A reflecting truncated layer, with positive acoustic impedance contrast, at its top, and a negative at its base, has been faulted and the two blocks have been displaced.
- Each severed edge of the marker acts as a separate layer and generates, outwardly, an hyperbola leg of the same polarity as the slab and, beneath it, one of opposite polarity to the marker.

Parasite diffractions can be associated with:

- Airwaves,
- Surface waves,
- Ambient noise (sea, Wind, boats, etc.)

Diffraction Characteristics

- Diffraction characteristics at two ends of the plate are:

PHASE SHIFT π

AMPLITUDE 0.5

- Reflection is ending on hyperbola tangent to reflection. The apex of which is:

a- Either at contact point, if reflector is horizontal

b- Slightly below, if reflector is dipping.

Fig. 87- This sketch illustrates the main characteristics of diffractions associated at the terminations of a sedimentary layer.

Polarity Inversion

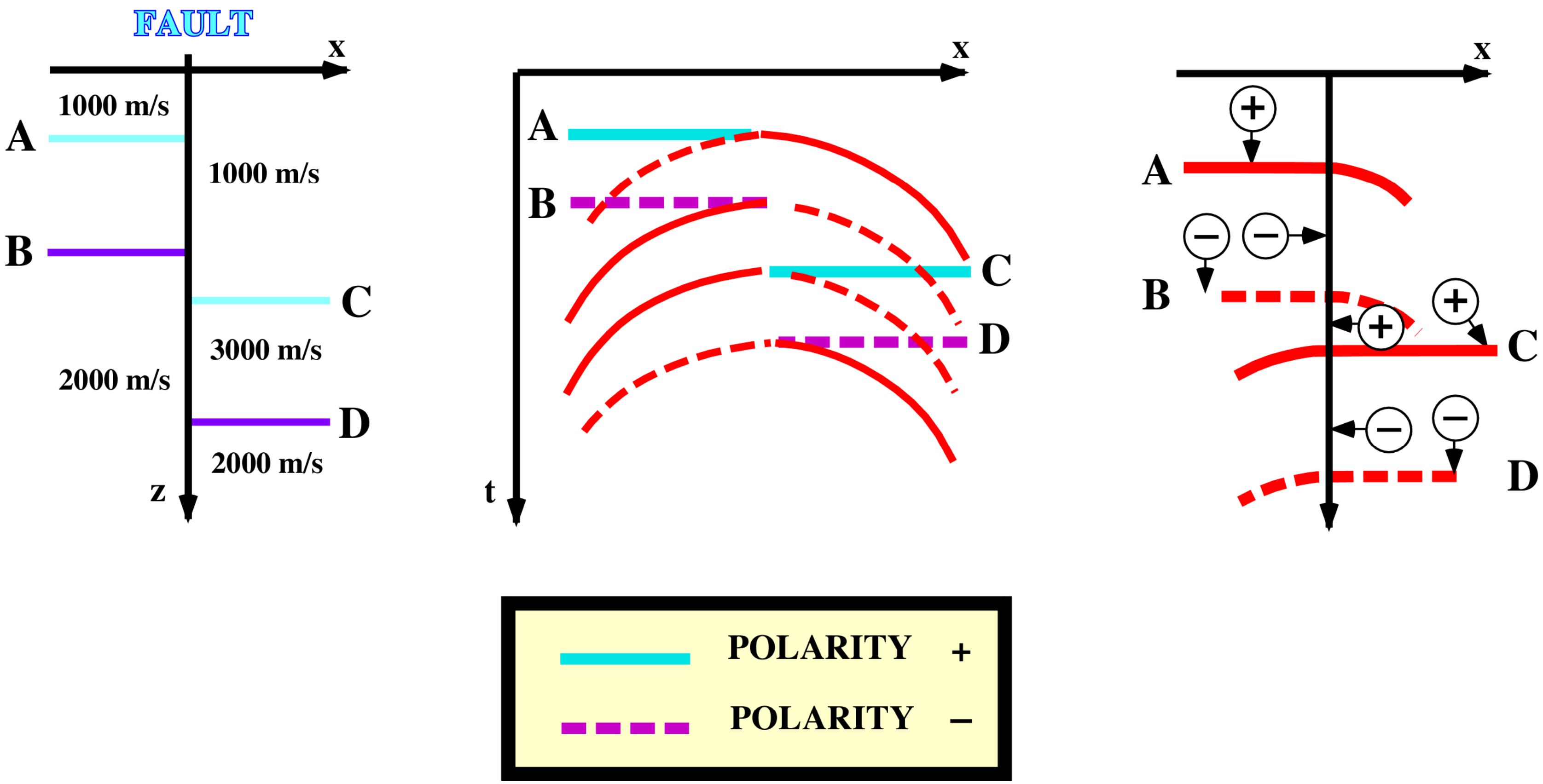


Fig. 88- Diffration characteristics in the case of a faulted layer.

E. 6) Reflected Refractions

In certain sedimentary basins, in order to avoid misleading interpretation of fault planes, the recognition of **reflected refractions** is of paramount importance, as in the North Sea. Figure 89 illustrates a typical example taken from a North Sea line. The reflected refractions are often straight lines arrivals. The slope of a reflected refraction as illustrated below (figs. 89-92), is dependent on the velocity of the refractor and its dip. Any structure in the refractor be will appear as departures from a straight line.

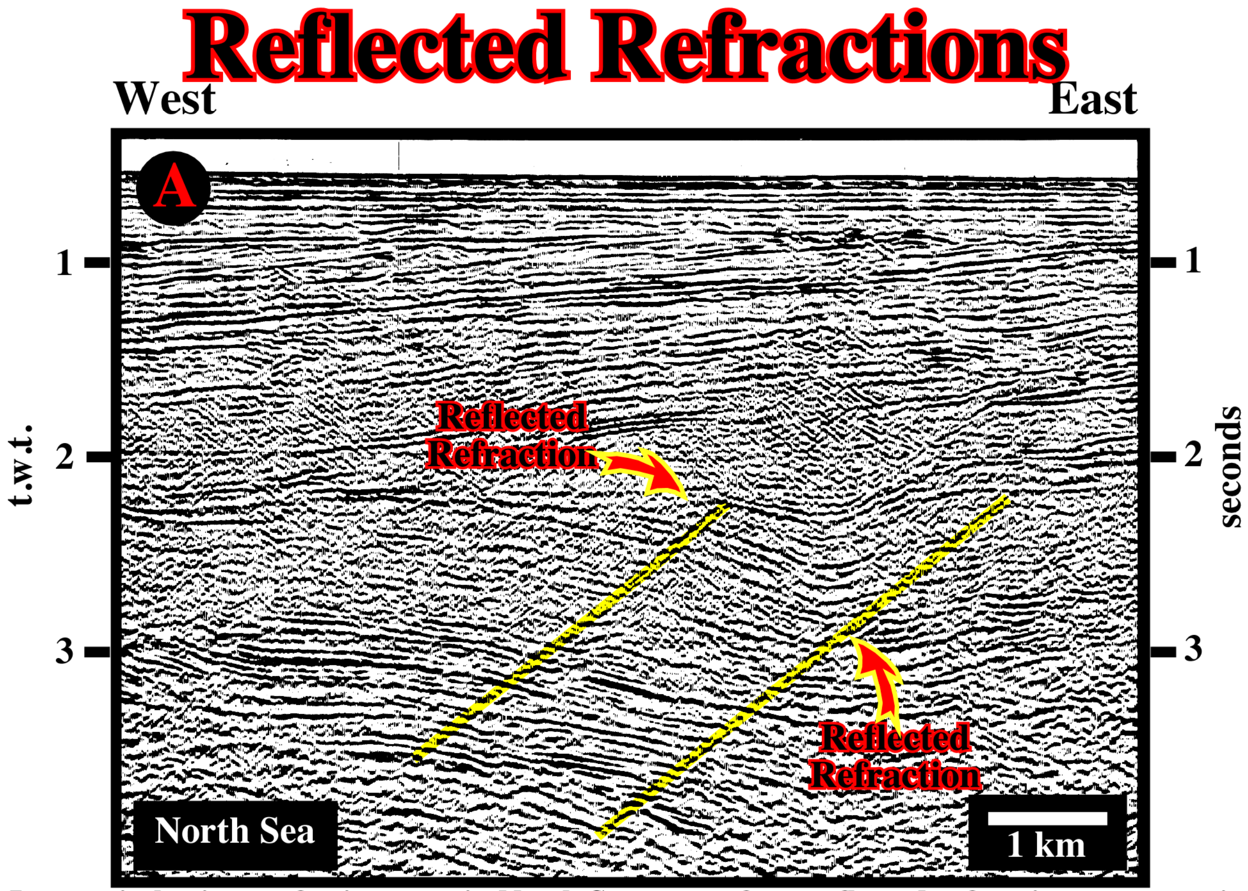


Fig. 89- In certain basins, as for instance in North Sea, very often, reflected refractions are associated with normal faults. However, they should not be interpreted as fault planes.

C.Cramez
Switzerland

Reflected Refractions

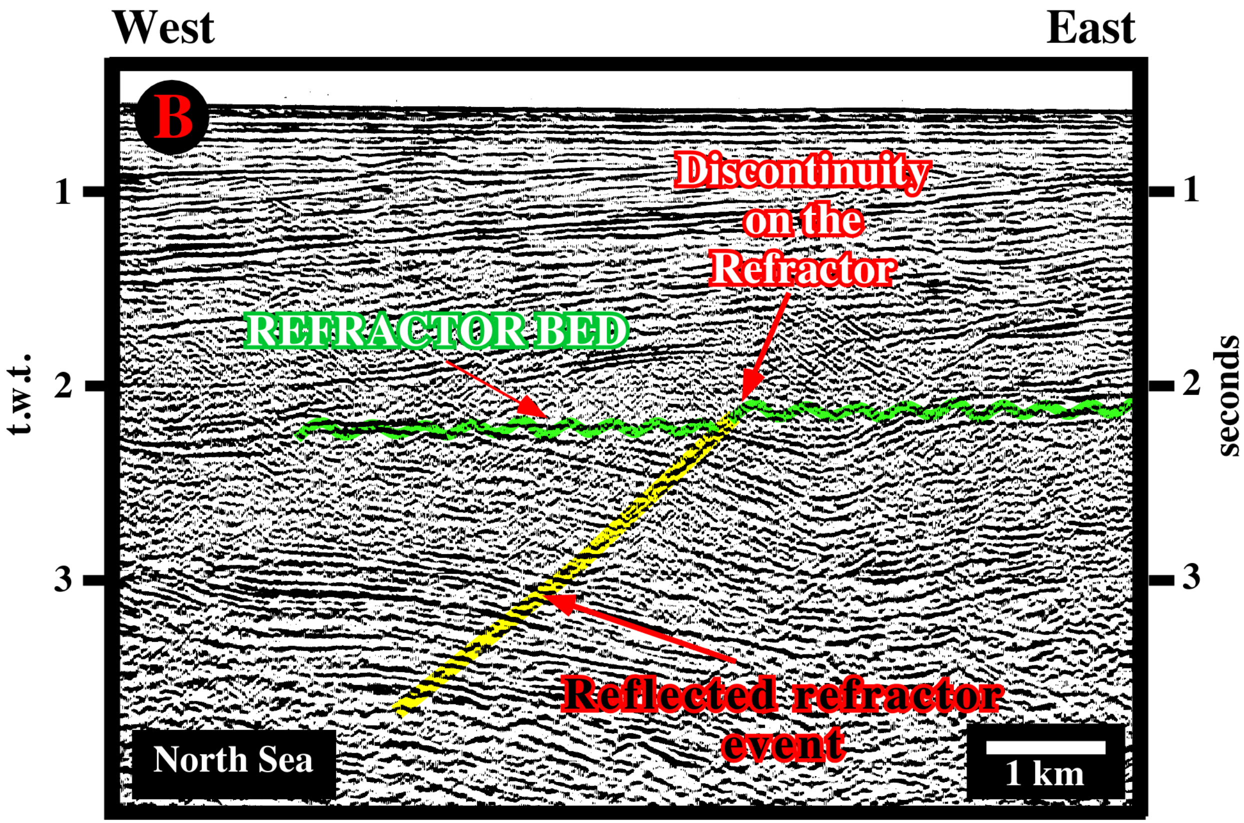


Fig. 90- On this migrated line it is quite evident the reflected refraction is associated with a normal fault affecting the refractor bed, which, in this particular example, corresponds to a major unconformity. Generally, in un-migrated lines, the reflected refraction is tangent to the diffraction hyperbola from the fault and it can only exist with the backward hyperbola. On the side of the forward hyperbola, the refractor does not exist at the same level. That explains why on this migrated line, we just see the reflected refraction dipping westward.

Reflected Refractions
&
Fault Planes

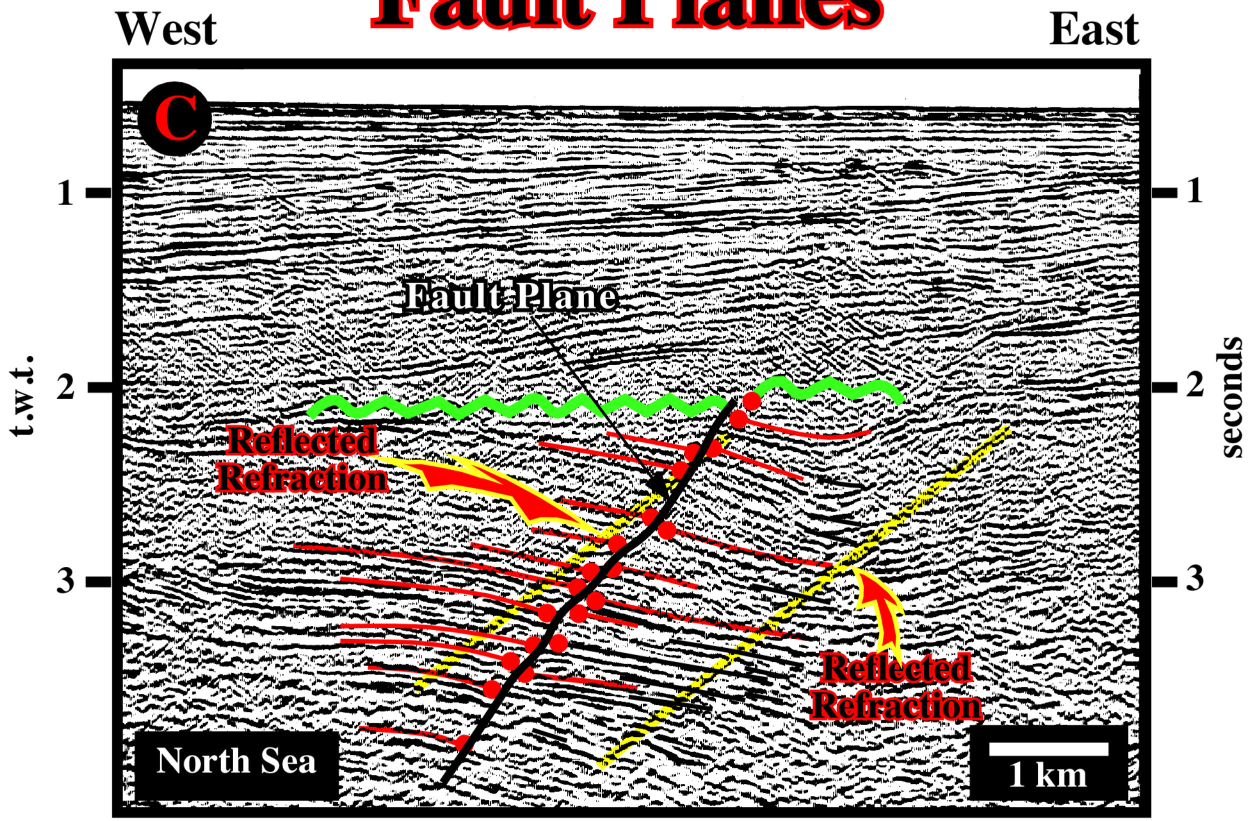


Fig. 91- Here, one can see the differences between a reflected refraction and the fault plane of the normal fault affecting the Mesozoic rift-type sediments of the North Sea. As depicted above, the reflected refraction (yellow) is rectilinear downward. Its slope is function of the compressional wave velocity of the refractor bed, that is to say, the higher the velocity of the refractor bed (in green) the higher the slope of the reflected refraction. On the contrary, as pictured, the normal fault plane (in black), emphasized by the reflections termination (red circles), shows changes in dip and its hade slightly increases with depth, since the compressional wave velocity of the sediments increases with depth. The dip changes of the fault plane are associated with lithological changes in the faulted blocks.

Reflected Refractions & Fault Planes

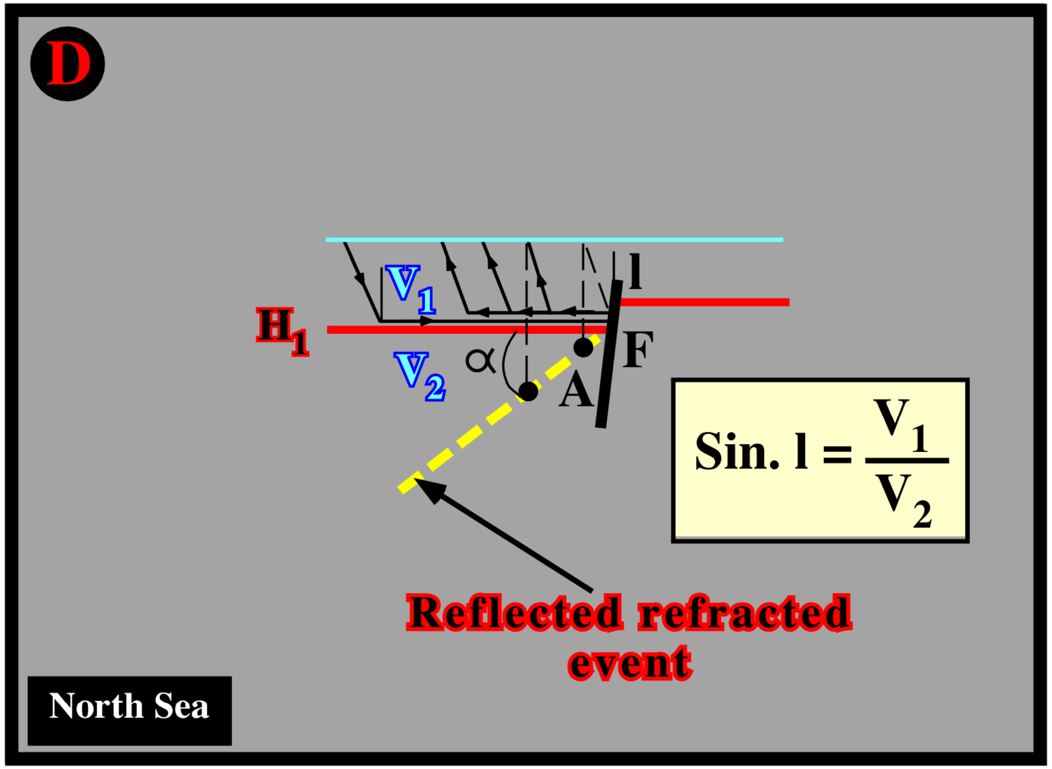


Fig. 92- The theoretical principle of the development of reflected refractions are illustrated above. Basically, the seismic waves arriving to the refractor bed H_1 (in red) are refracted along it until finding the discontinuity created by the normal fault F. Arriving at the discontinuity point, the waves are reflected backward along the refractor and upwards till the receiver. Subsequently, on a seismic line, the reflected refractor event will be depicted as a more or less continuous rectilinear reflection (yellow) dips toward the hangingwall of the normal fault. The dip of the reflected refracted event is a function of the velocity of the refractor.

The reflected refraction will be tangential to the diffraction at the critical distance:

- Larger amplitudes can be expected in the neighbourhood of the critical distance.

Reflected refractions can appear only on the backward-direction hyperbola. In the forward direction, the refractor does not exist. Still another fault arrival is a simple reflection from a fault plane. It is necessary that the elastic properties of the two rocks separated by the fault differ sufficiently strongly:

- For the fault reflection to be traced very far, the contrast must be maintained along the fault.

- If this is not met, the fault-plane reflection will vary so much in amplitude and character that the continuity will be impaired.

Some fault plane reflections are so persistent in continuity and so regular in character even while cutting a great thickness of varied sediments, that one is led to the conclusion that the fault-plane itself has lithological characteristics, which contrast strongly with those of the enclosing rocks:

(i) Fault plane between **sediments and basement** rocks;

(ii) Fault plane **injected** by intrusive rocks;

(iii) Fault **gouge water-saturated** or gas-cut;

(iv) Fault plane filled with **sandstone dykes**;

(v) Fault plane with **mineralized veins**;

(vi) Fault plane with **salt** ("fault weld"), etc.

In normal geological conditions, there are not primary seismic reflections associated with the fault planes. In practice, the picking of a fault plane, on a seismic line, obeys certain interpretations rules, since a fault corresponds to a more or less abrupt **discontinuity of sedimentary layers** along which appreciable displacement has taken place.

a) The first steptofault picking is to locate the reflection terminations that emphasize the geometry of the fault plane as illustrated in fig. 91.

b) As shown in fig. 91, the geometry of a fault plane, in the ground or on seismic lines, in general, is not rectilinear.

- The **dip of the fault plane** changes along its plane as a function of rheologic behaviour and compaction of the sedimentary layers.
- Such irregular geometry contrasts with the **rectilinear geometry** of the reflected refraction, in which the dip of the reflection emphasizes the velocity of the **refractor bed**.
- Reflected refractions and fault planes, recognized on North Sea seismic lines, are illustrated on figs. 90 and 91.
- In addition, as a seismic line is a time section, it is physically impossible to have a fault geometry rectilinear.

Fig. 92 illustrates what happen when the reflector is a strong one, with a positive reflection coefficient (i.e. when a low velocity rock overlies a high velocity rock):

- As the observation point moves further from the fault, the angle of the direct path from the diffracting point to the reflector eventually falls below the critical angle.
- At this distance there are two arrivals.
- The direct one is a wide-angle diffraction.
- The second is a reflected refraction - refracted in the high velocity rock, reflected from the fault face.

E. 7) Static Corrections

Reflection times on seismic traces, recorded on land, have to be corrected for time differences introduced by **near-surface irregularities**. These irregularities have the effect of **shifting** reflection events on adjacent traces out of their true time relationships. The two major sources of irregularity are:

1) **Elevation differences** between individual shots and detectors, and
2) The presence of a **weathered layer**, which is a heterogeneous surface layer, a few meters to several tens of meters thick, and of abnormally low seismic velocity.

These two major sources of velocity irregularities are sketched in fig. 93.

Static Corrections

a) Necessary to get rid of surface topography on time section.

b) Necessary to get rid of weathered-zone if any on time section.

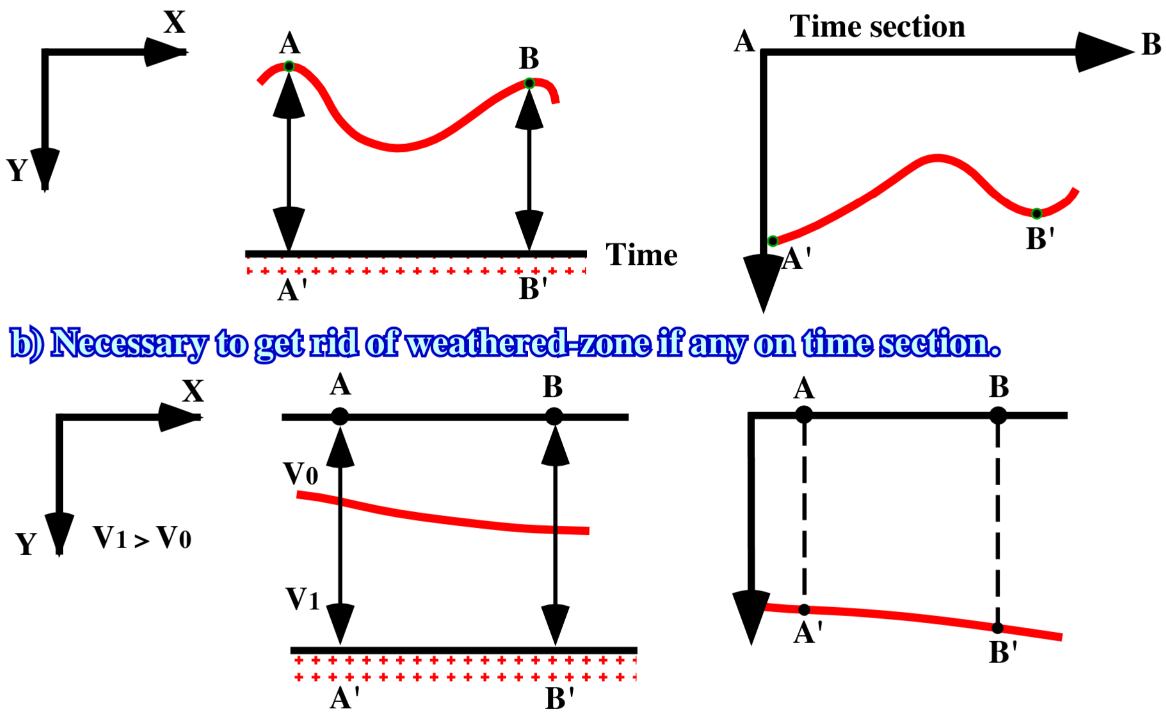


Fig. 93 - Static corrections take into account the topography and the weathered-zone as pictured above.

The static corrections are a combined **weathering** and **elevation correction** that removes the effects of low velocity surface layer and reduces all reflections to a common datum. Changes in water depth induce typical parasites, particularly on the distal parts of the seismic lines of continental platforms, and in the upper slope, where, often, submarine canyons are often carved by turbiditic currents. A sharp chang in water depth, such as illustrated in fig. 94 induces a lateral variation of the velocity interval. The seismic waves are retarded progessively deeper water and the time-traject will be longer. Hence, the associated reflections are pulled-down below the greater water depth.

Seismic Example

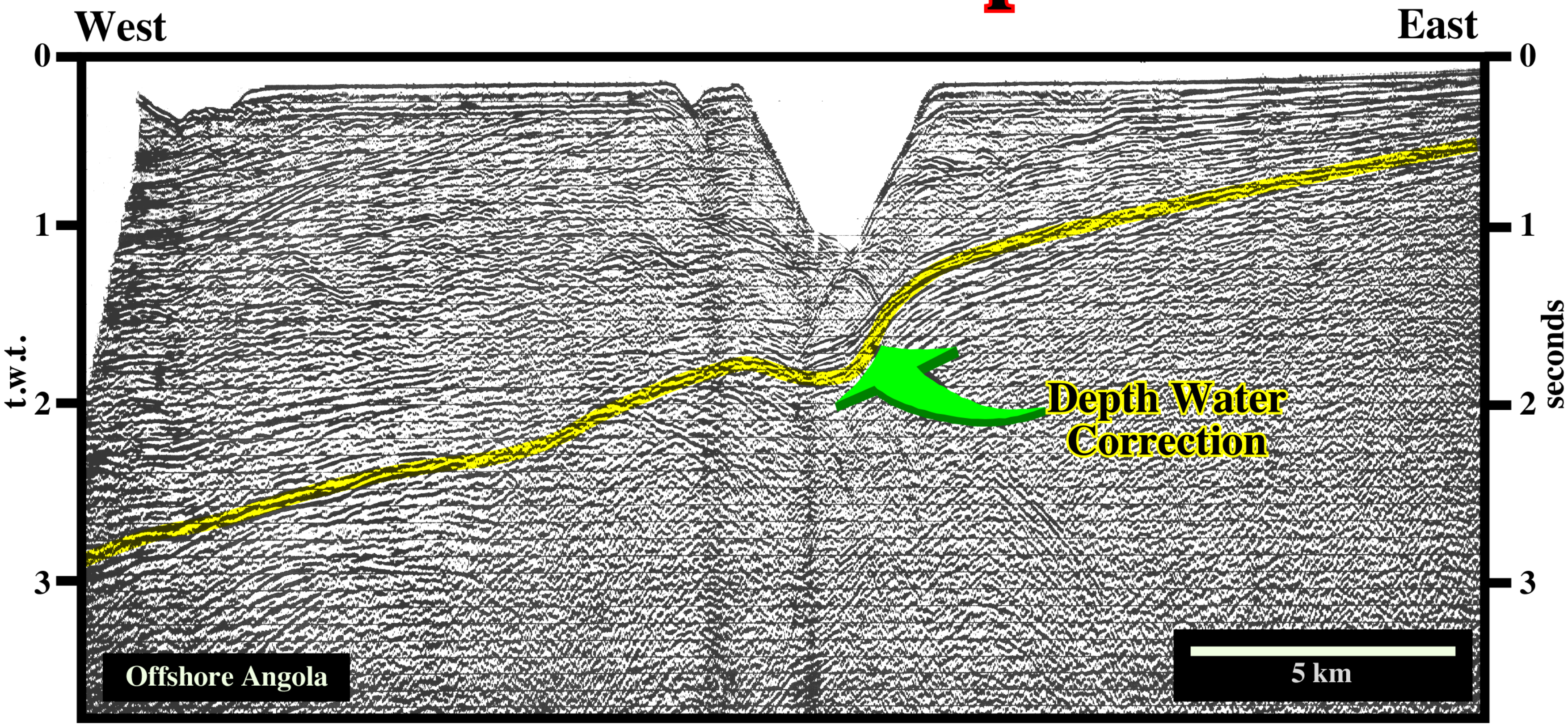


Fig. 94- On this seismic line, from the northern offshore Angola, nearby the Congo river, the water-depth variation induces local pull-down of uniformly continuous reflectors. Indeed, seismic waves travel slower through water than through sediments. The pull-down of the reflectors directly below the Congo submarine canyon is evident. However, it does not have any geological meaning. In a depth section the reflectors keep the regional seaward dip recognized all along the profile.

F) Geological Models & Seismic Responses

Since current data processing and interpretation yield seismic sections resembling geologic cross-sections, inexperienced geologists and geophysics are often greatly tempted to read geology more or less directly from the seismic data. Unfortunately, as seen previously, serious errors may result in such an approach. This is especially true in areas of complex tectonics (high dips), rapid changes in lithology (density and velocity), irregular surfaces and complex near surface conditions. The following geological models and their time responses indicate why so many errors are frequently found in geological interpretations of seismic lines:

F.1- Monoclines

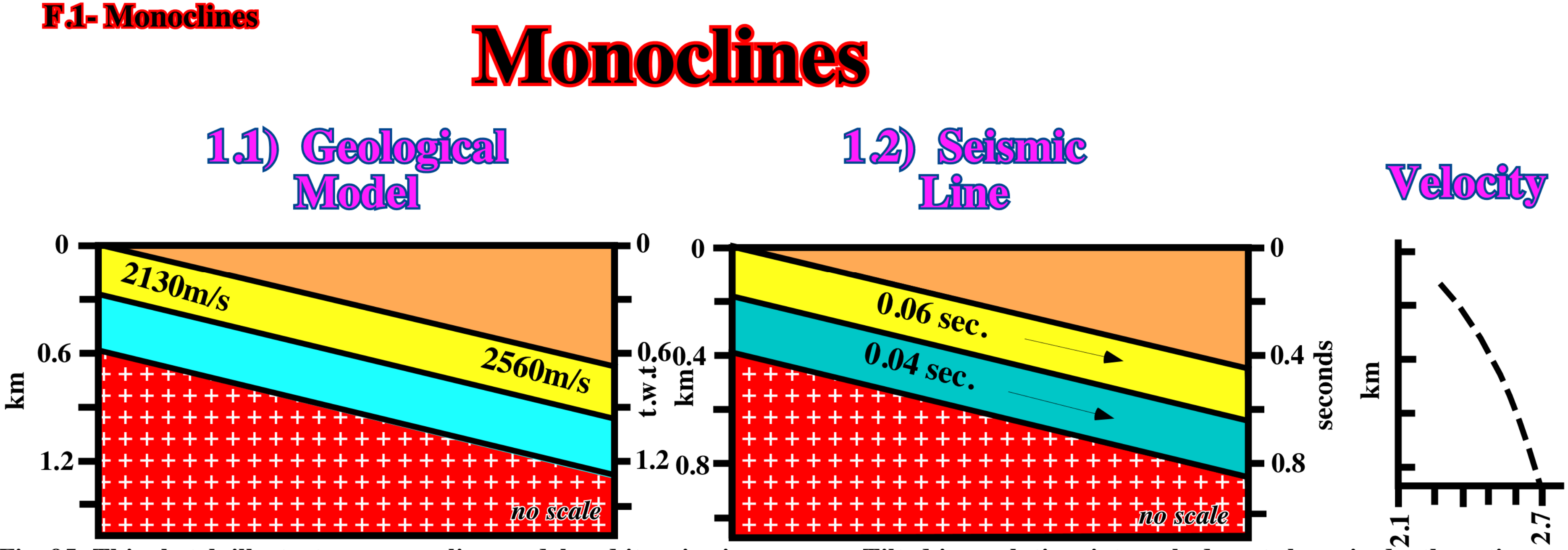


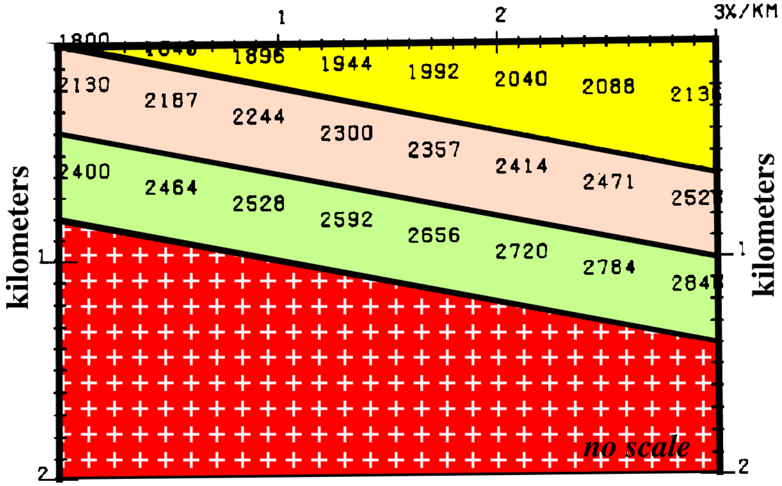
Fig. 95- This sketch illustrates a monocline model and its seismic response. Tilted isopach time intervals do not show, in depth sections, a constant thickness, except when the tilting (sedimentary or tectonic) is post-compaction.

Actually, since the tilting is pre-compaction, there is an increasing of the velocity interval with depth, hence one can say, in time seismic lines (by far the more used) a constant time-thickness emphasizes an increasing depth-thickness, as the velocity interval is greater in the more buried sediments.

A mathematical geological model of a pre-compaction tilted stratigraphic column and its wave equation seismic response are illustrated below (fig. 95). The time thickness of each sedimentary package is thinning downdip. However, in the mathematical depth model the thickness is constant, just the velocity interval increases downward.

Monoclines

1.3) Mathematical Model



1.4) Seismic Response

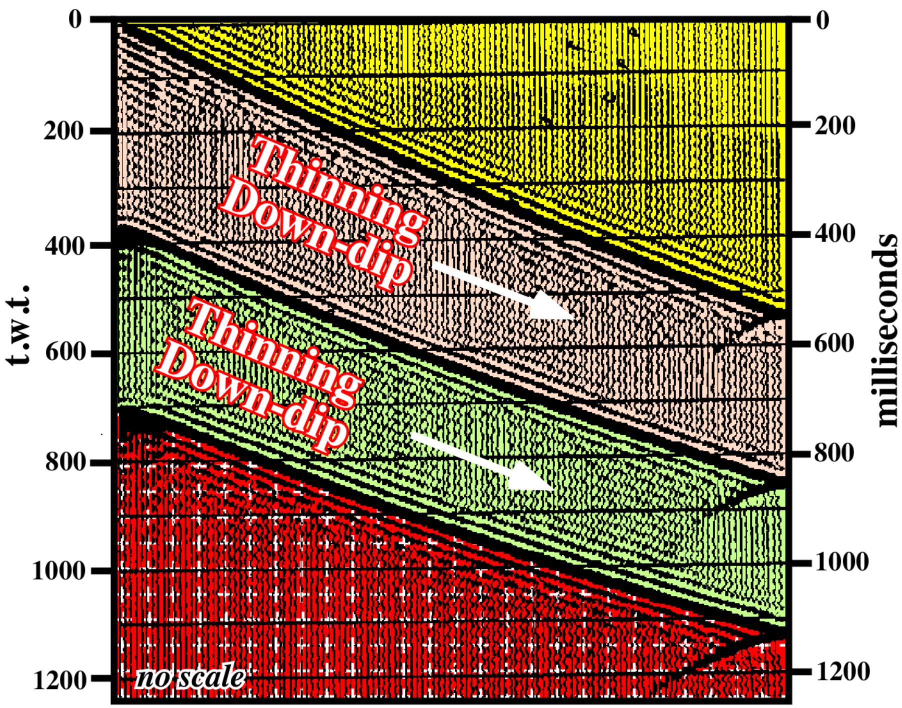


Fig. 95- In the mathematical model, three isopach interval are considered. However, in each interval, due to differential burial the compressional wave velocity increases down-dip. In the uppermost interval (yellow), the velocity ranges from 1804 to 2136 m/s. In the second interval (rose), the velocity is higher; it ranges from 2130 m/s in the less buried sediments, to 2520 m/s in the more deeply burried sediments. In the green interval, overlying the basement, the velocities change from 2400 to 2840 m/s. In spite of the fact that in the model, the intervals are isopachous, they are thinning down-dip on the seismic response.

F.2- Normal Faults (Growth Faults)

On a seismic line, the majority of the normal faults have a geometry similar to that illustrated on fig. 96, that is to say, the reflector of the up-thrown block, below the fault plane, is pulled down, while on the ground, or in the geological depth model (see below) the reflectors are horizontal.

Normal Faults

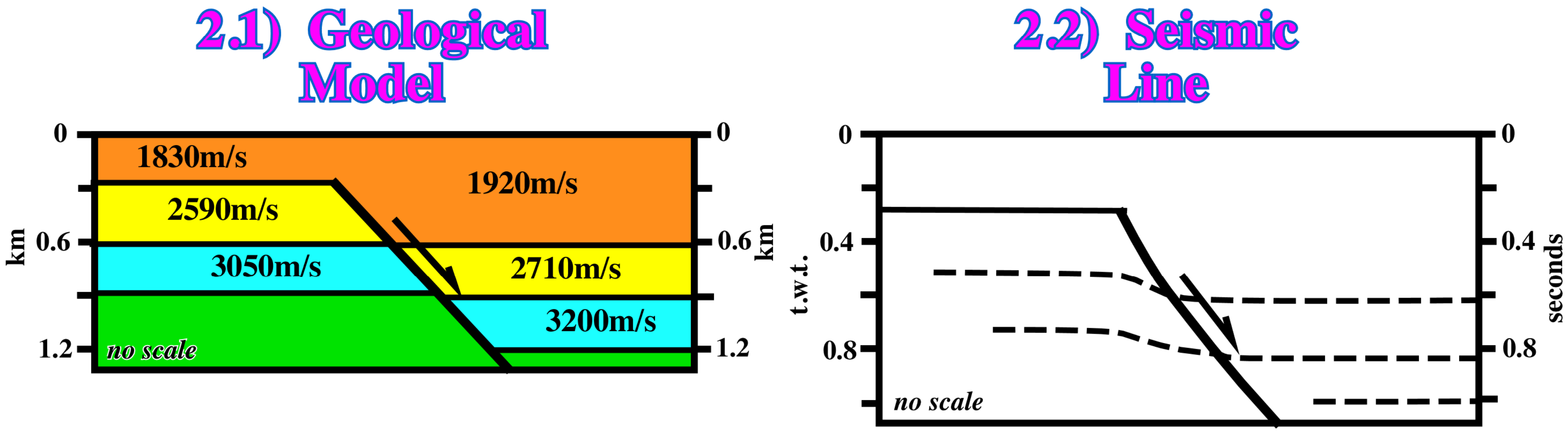


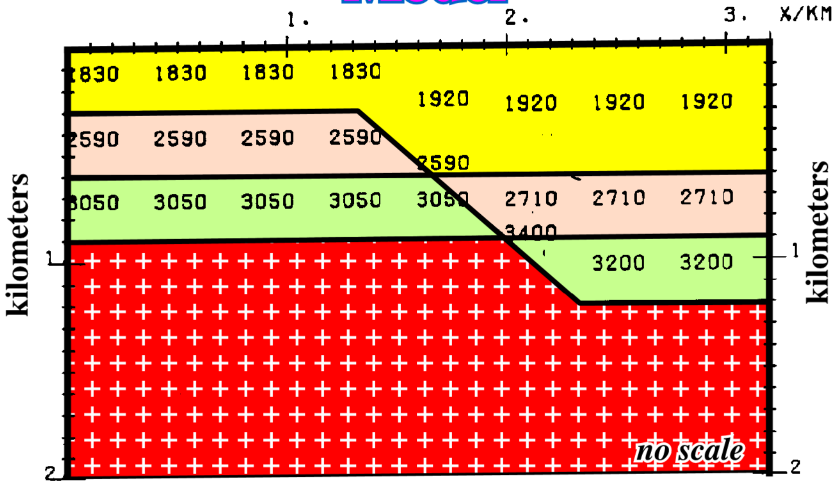
Fig. 96- Above, a geological model of a normal fault and its seismic response are illustrated. Theoretically, due to the downward relative movement of the hangingwall, intervals with quite different interval-velocities are juxtaposed, which has important consequences on the seismic response: the footwall reflectors below the fault plane (area of a lateral velocity changing) will be pulled down, since, at same level, the velocity interval in the hangingwall is smaller.

The explanation of this misleading geometry is easily explained in fig. 97. Indeed, due to the fault movement, there is juxtaposition between high velocity sediments of the up-thrown faulted block and lower velocity sediments of the down-thrown block.

This seismic artifact, induced by lateral changes in the interval velocity, is easily recognized on seismic lines, as illustrated on the seismic line from offshore Angola (fig. 98). Indeed, as the sediments of the down-thrown block of the fault-growth have a lower velocity (mainly shales) than the sediments of the up-thrown block (mainly carbonates), not only the reflections below the fault plane are pull-downed, but the reflection associated which the salt weld as well as (down-throw block).

Normal Faults

2.3) Mathematical Model



2.4) Seismic Response

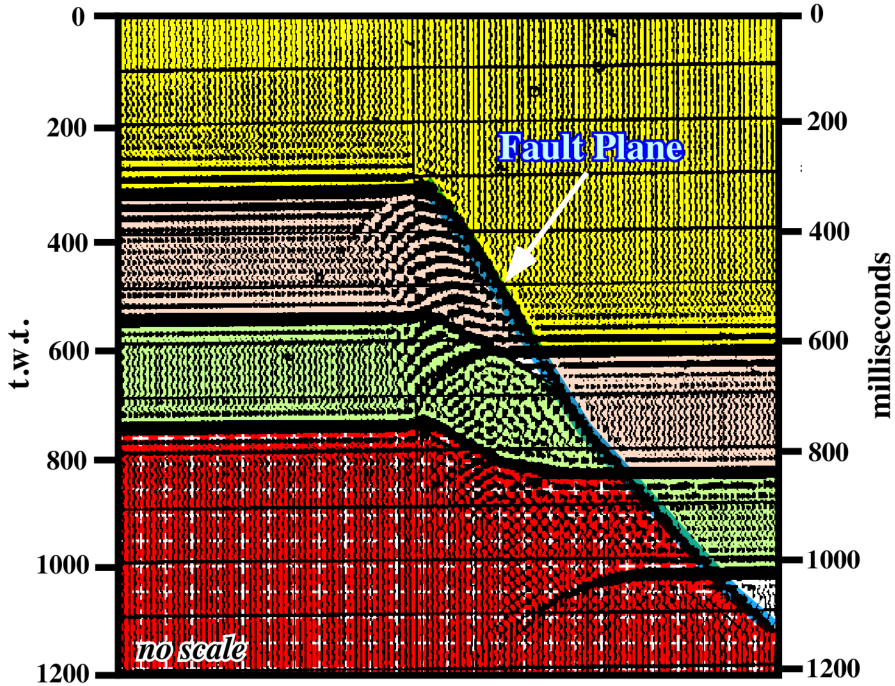


Fig. 97- On the mathematical model, three sedimentary intervals are considered above the basement. All intervals are affected by a normal fault. Hence, the sediments of the hangingwall (down-thrown faulted block) are denser. They reached higher depths. Therefore, their compressional wave velocities are higher than the sediments of the footwall. Subsequently, on the seismic response, the reflectors of the footwall are pulled-down below the fault plane, where there is a lateral change of interval-velocity.

Seismic Artifact
induced by
Normal Faulting

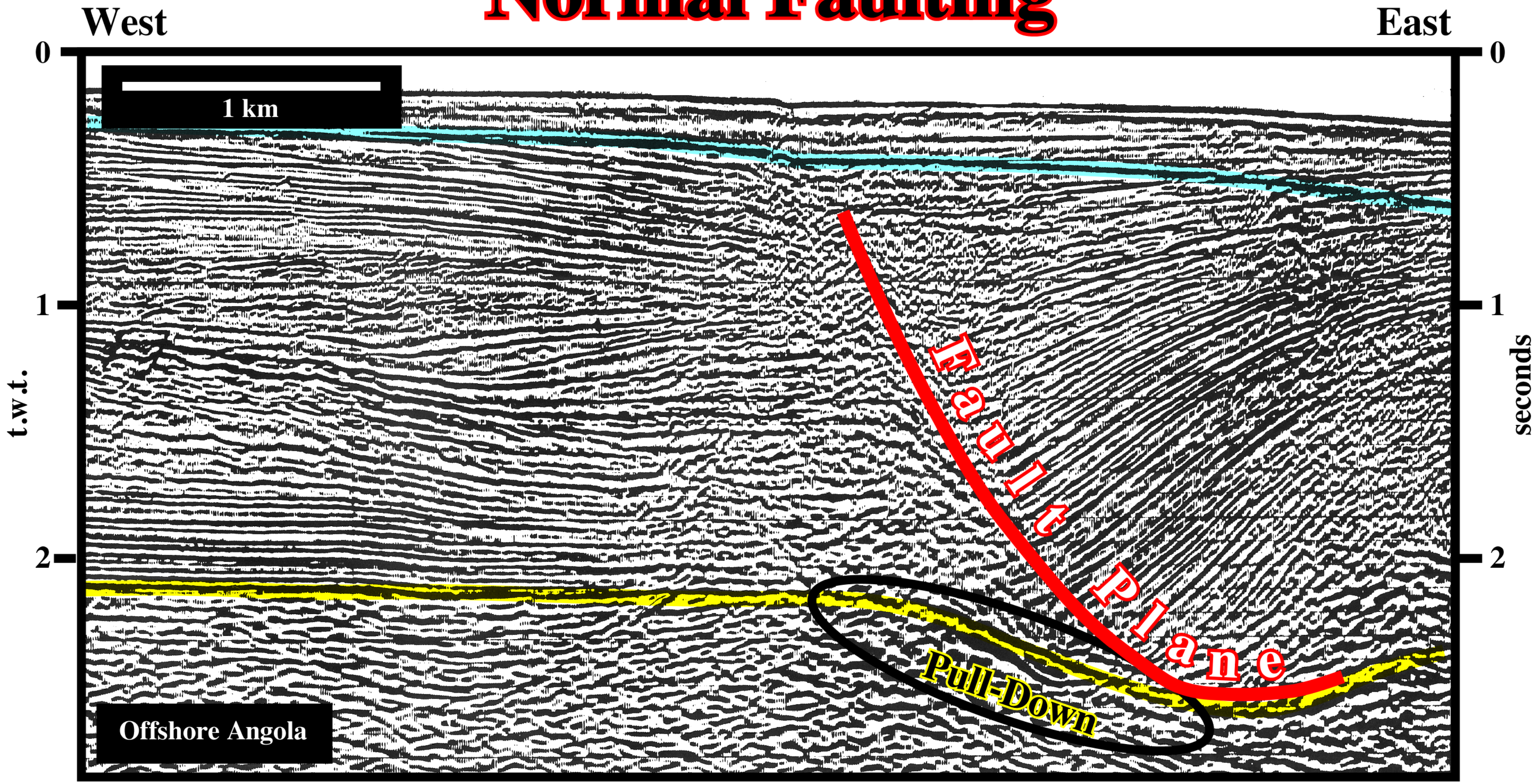


Fig. 98- On this seismic line, from offshore Angola, the pull-down of the yellow marker (bottom of the evaporitic interval) is induced by the lateral change of the interval-velocity created by the normal fault which limits a Upper Tertiary depocenter. Indeed, such a fault put limestones (up-thrown block) and shales (down-thrown block in juxtaposition.

F.3- Reverse Faults (Thrust Faults)

As shown in the geological model below, the geometry of the different sedimentary facies is parallel and horizontal and the interval-velocities are laterally constant. On the other hand, due to the fault movement, the up-thrown block was uplift, and so, sedimentary packages with different velocity intervals are juxtaposed.

Reverse Fault

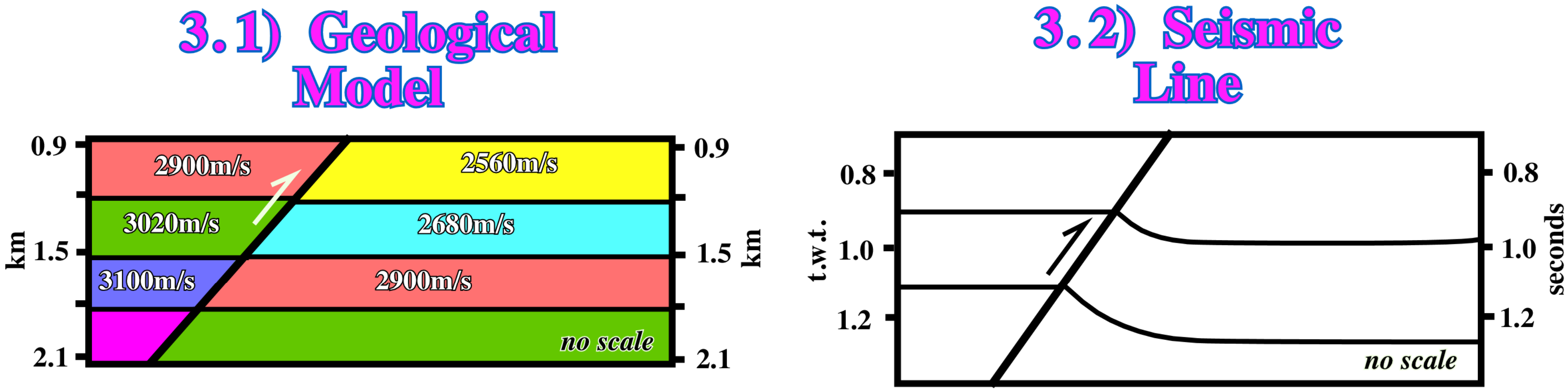


Fig. 99- Above, the geological model of a reverse fault and its likely seismic response is depicted. As illustrated, the reflectors of the footwall are pulled-up due to a lateral change of the interval-velocities.

The principal consequence of the lateral, and abrupt changing of the velocity interval is the pull-up of the seismic reflectors below the fault plane, that is to say, of the footwall. Fig. 100 illustrates the velocity model used to find the more likely seismic response (time) of the previous model.

It is particularly important to notice that on a seismic line, the trace of the reverse fault plane is not emphasized by an obvious reflection, but marked by the discontinuities between straight dipping reflector (on the right) and the pulled-up reflectors on the left (hangingwall). In other words, interpreters should not interpret the pull-up of the reflectors as a geological uplift associated with a compressional tectonic regime (i.e. as an antiform trap, for instance).

If you have doubts, to decide between a pull-up and a structural tectonic feature, do not forget that a depth conversion can solve the problem:

(i) If, the antiform like feature disappears on the depth-converted section that means that it was a pull-up induced by a lateral velocity change.

(ii) If, on the contrary, the antiform like structure persists on a depth converted line, it may be interpreted as sedimentary shortening in the footwall .

Reverse Fault

3.3) Mathematical Model

3.4) Seismic Response

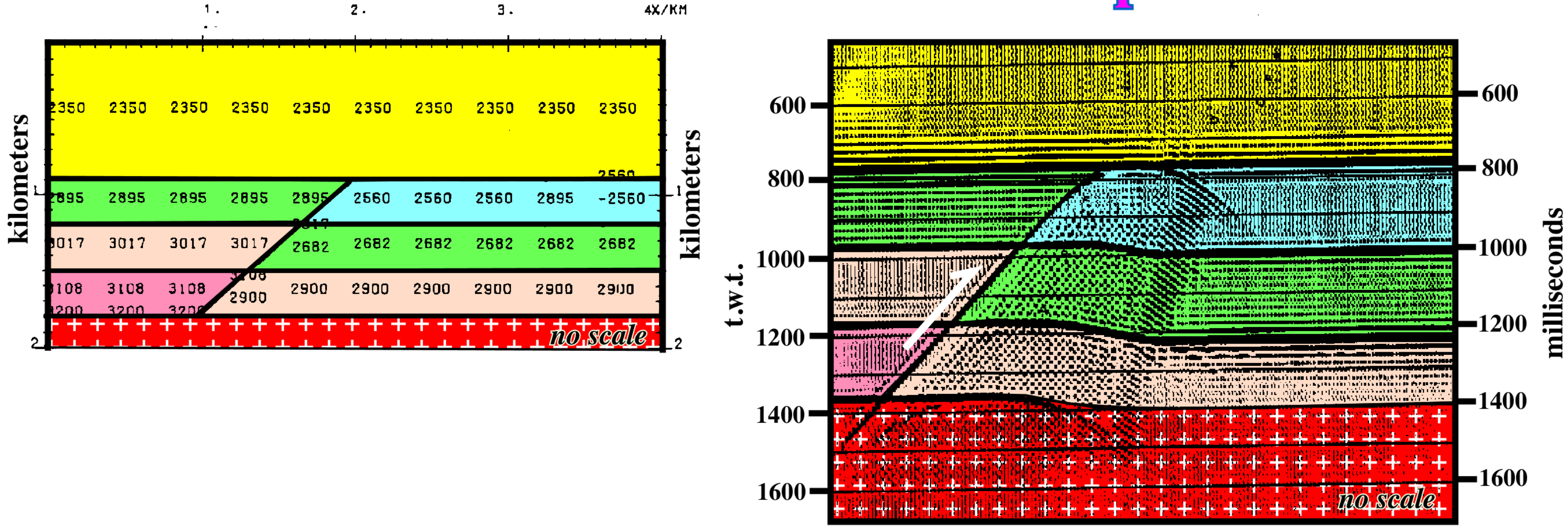


Fig. 100- The seismic response of a mathematical model of a reverse fault, in which the sediments of the hangingwall are denser than those of the footwall, corroborates the hypothesis that the reflectors below the fault plane are pulled-up creating the common illusion of an anticline structure (see fig. 101).

Seismic Artifact
induced by
Reverse Fault

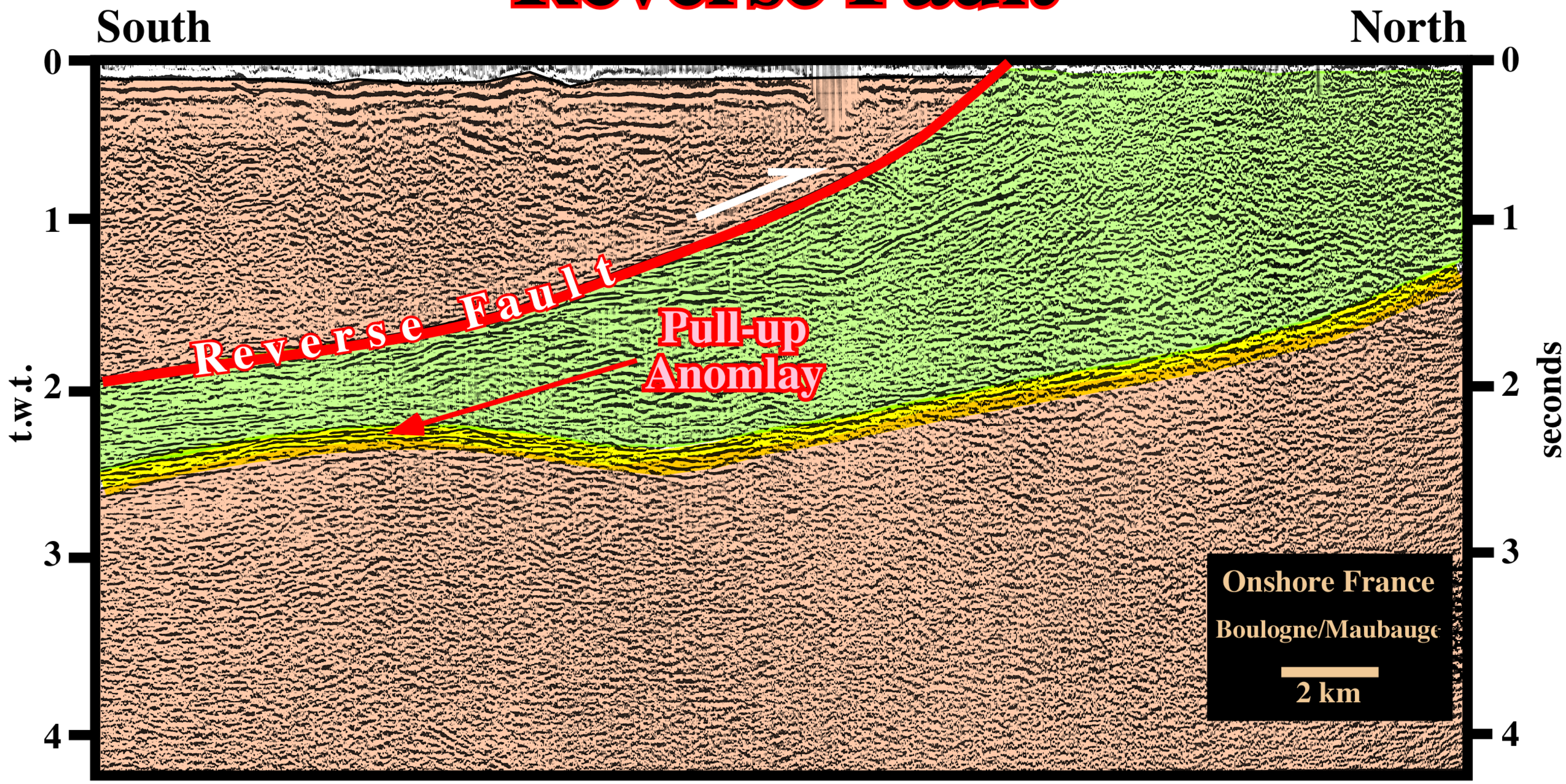


Fig. 101- This seismic line from onshore France illustrates a seismic artefact associated with a thrust fault, that is to say, an apparent anticline structure under the reverse fault plane. In spite of the evidence of the seismic pull-up, "explorationists" drilled a wildcat on such an artifact thinking that they were testing a large under-thrust structural tras. Actually, in certain basins, as we will see later, there are prolific petroleum traps under reverse and thrust faults, hence explorationists must always test their interpretations by time-depth conversions.

If you recognize an antiform feature in the footwall block of a reverse fault you must admit two possibilities: (i) a **seismic artifact** and (ii) an **anticline**. Then, you must imperatively test both hypotheses and reject the one which is falsified by testing. In petroleum exploration, avoiding such scientific tests can be highly dangerous and expensive.

Cusiana Structure

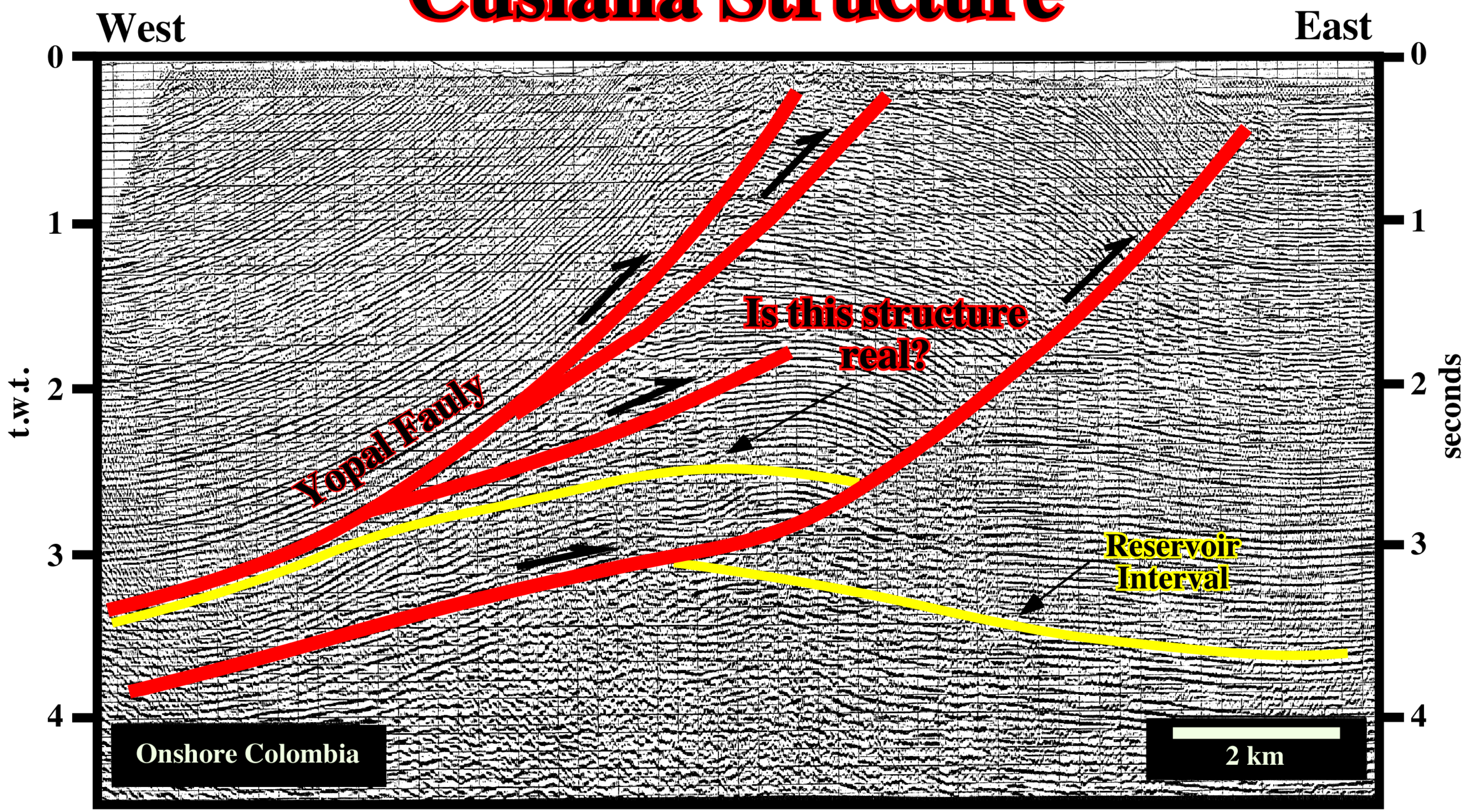


Fig. 102- This seismic line through Cuisiana #2A (discovery well), in the Colombia foothills, was drilled by an international consortium composed of BP, Total and Triton, in order to test the anticlinal structure under upper thrust-faults. However, before drilling, several time-depth conversions corroborated the hypothesis advanced by certain explorationists that the sub-thrust antiform was a real compressional structure and not a seismic artifact induced by the hanging wall.

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Switzerland

The Cusiana prospect, which is located on the footwall block of a very important reverse fault, the Yopal fault, was proposed by Triton, who held 100% of the exploration rights, to several major oil companies. However, the majority of the companies interpreted the structure as a **pull-up** due to a lateral velocity change induced by the Yopal fault, and refused Triton's farmout. Fig. 103 illustrates a typical example of how seismic artifacts can be tested by a time depth-conversion. These examples from the Colombian onshore clearly illustrate the danger for explorationists to make strategic decisions without testing all proposed geological hypothesis.

Seismic Example
(onshore Colombia)

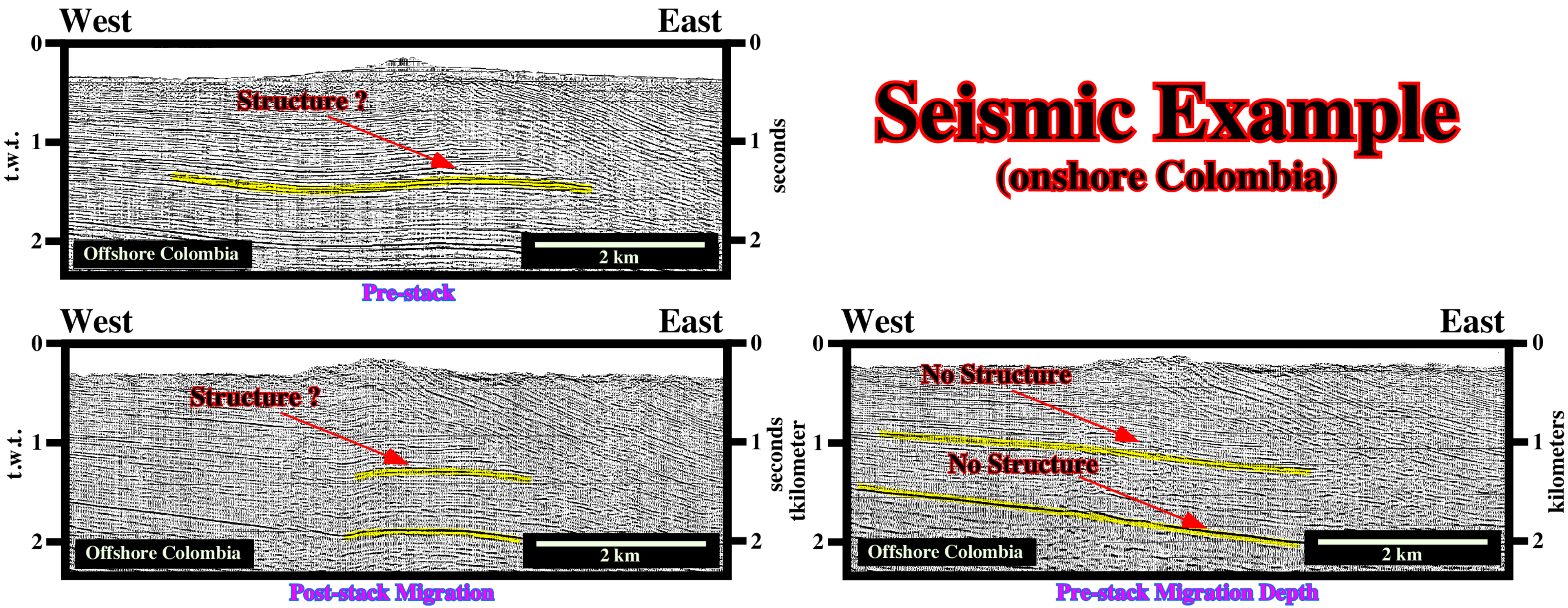


Fig. 103- Note all time-depth conversions corroborate anticline structures below the thrust faults. In this particular example, coming, as the previous line, from the Colombia foothills, a nice antiform structure (that is to say a potential structural trap) is recognized on the pre-stack section. The same potential structure is also recognized on the pre-stack migrated version, just under the fault plane, which should make the interpretation questionable. Finally, the pre-stack migrated depth versions strongly falsify the hypothesis of a sub-thrust structure. Actually, the sub-thrust sediments are undeformed and not shortened.

F.4- Shale Diapirs

A shale dome's geometry (fig. 104) induces important lateral and vertical changes in velocity intervals. Due to diapirism, low velocity sediments will be pushed-up and juxtaposed to higher or lower velocity sediments. So, a planar bottom of a shaly facies, either horizontal or tilted on time seismic, generally has a pull-down geometry (fig. 104).

Shale Diapir

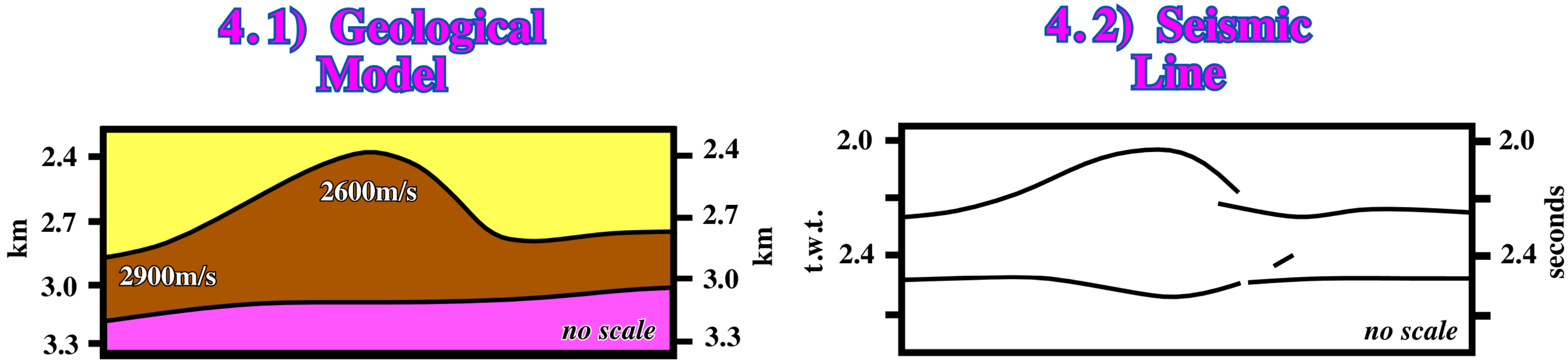
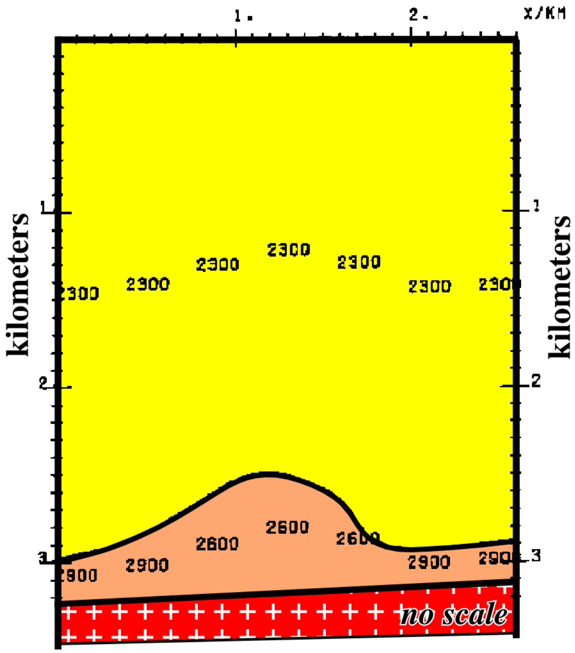


Fig. 104- On this figure are illustrated a geological model of a shale mound and equivalent seismic line. In the geological model, the shale interval (brown) has velocities ranging between 2600 and 2900 m/s.

In the majority of the cases, unfortunately, it is very difficult to see the root of the shale domes. Similarly, on un-migrated lines, due to the complex geometry of the reflections associated with the top of the shale, only the uppermost part, that is to say, the apex of the reflection associated with the domes, is in its real time position. In certain evaporitic basins, salt and shale domes can be present with similar geometries. One of the best ways to differentiate them is to look at the seismic markers emphasizing their bottoms. As stated previously, generally, the base of a shale dome has a pull-down geometry, while the bottom of salt dome shows a pull-up geometry. However, the bottom of salt domes are easier to recognize.

Shale Diapir

4.3) Mathematical Model



4.4) Seismic Response

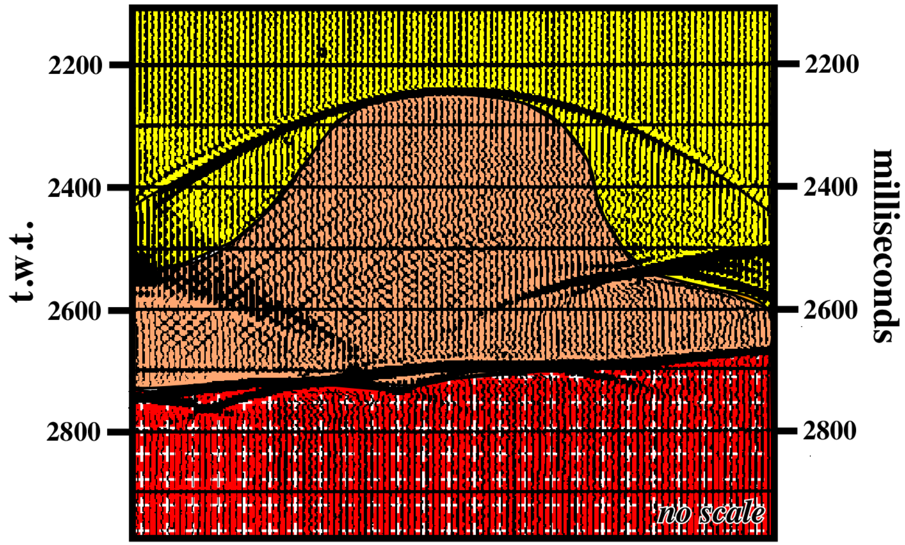


Fig. 105- In the velocity model, the yellow sediments above the shale mound have a constant velocity of 2300 m/s. The velocity in the shale interval is 2600 m/s in the upper part, and 2900 m/s in the lower part. The seismic response of such a mathematical model indicates that the velocity contrasts are not big enough to significantly pull-down the bottom of the shale interval directly below the apex the vertical of the mound. Notice the seismic response is un-migrated, so only the apex of the mound is in its real position.

F.5- Salt Diapirs

An interpreted seismic line of a salt dome and the correlative depth conversion (fig.106) clearly illustrates the seismic anomalies associated with salt thickness variations.

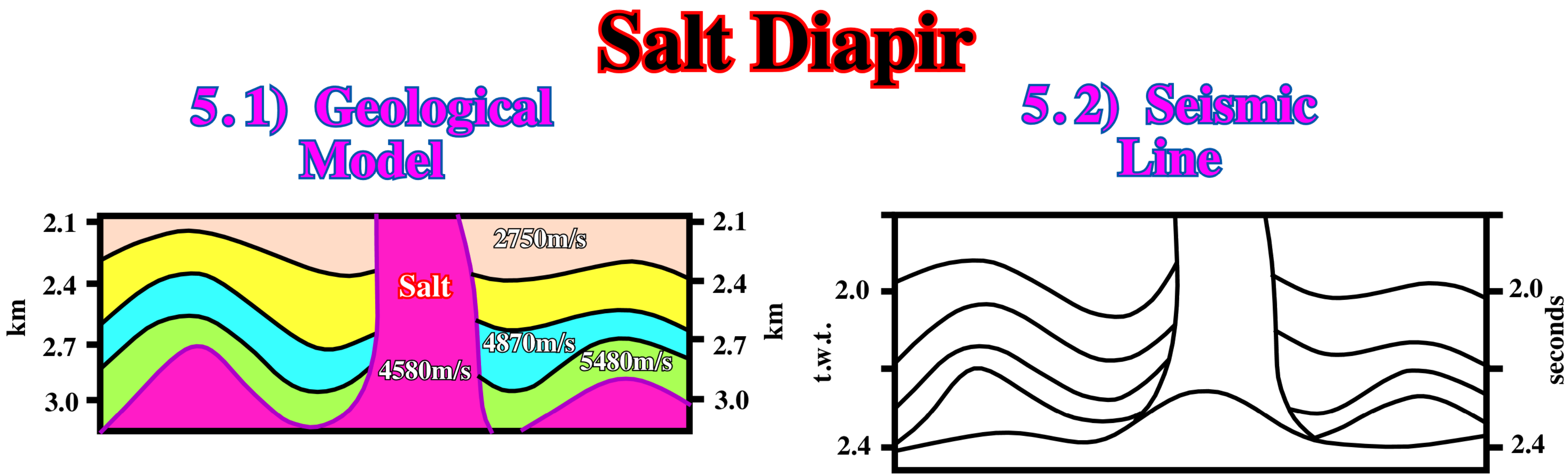


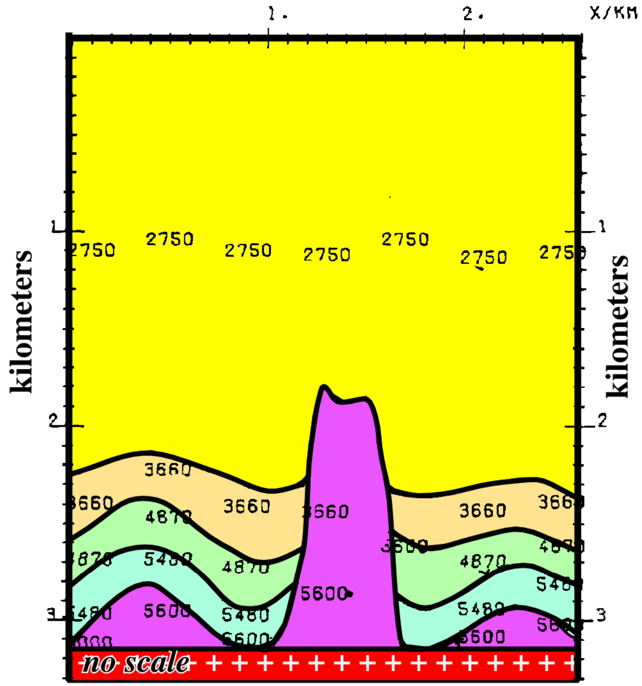
Fig. 106- In the geological model, the compressional wave velocity of the salt is constant and equal to 4580 m/s. The density of the salt ranges between 2.15 and 2.17 g/cm3. In addition, salt cannot be compacted, that is to say, its density is constant and so its velocity does not change in depth. The velocity interval of the suprasalt strata is supposed to be laterally constant. On the seismic line of such a geological model, illustrated on the right, the bottom of the salt layer is undulated. It is pulled-up under the thick salt.

In this particular example the salt interval, which has a velocity of 4580 m/s, is overlain by sediment with calcareous facies that has a high compressional wave velocity (around 5480-4870 m/s). So, when the salt flows laterally, locally is thinner, hence, the result is a pull-down of the reflectors (salt velocity is relatively slower than the limestones velocity). On the contrary, when there is an upward movement of the salt, it is juxtaposed to sediments with a lower compressional wave velocity and the final result is a pull-up of the reflector associated with the bottom of the salt. In other words, when a salt layer is not isopachous, the bottom of the salt is pulled-up at under the thick salt zones and pulled-down where the salt is thin or not present (salt weld).

A velocity model and its correlative seismic answer (fig. 107), clearly illustrate the causes of apparent wavy geometries on the bottom of evaporitic packages on time lines (un-migrated or not).

Salt Diapir

5.1) Mathematical Model



5.2) Seismic Response

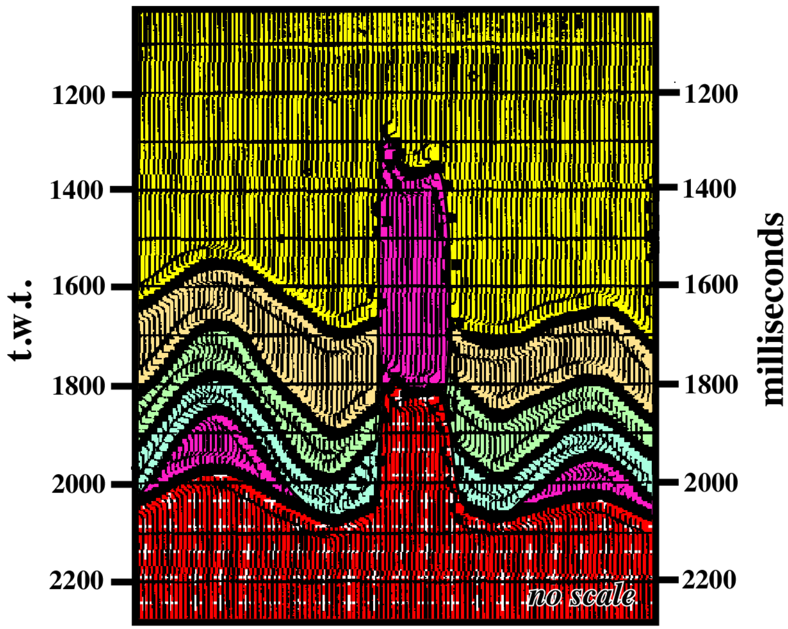


Fig. 107- The seismic response to the geological model is quite evident. The bottom of the salt, particularly under the apex of the salt dome, is pulled-up almost 0.2 seconds (t.w.t.). Similarly, the salt welds (absence of salt due to lateral and vertical flowage) are slightly pulled-down. Note that this geological model of a salt dome with vertical flanks is unrealistic. Actually, due to the fact that salt cannot be compacted, salt structures with vertical flanks are physical impossibilities.

Seismic Artifact
induced by a
Salt Dome

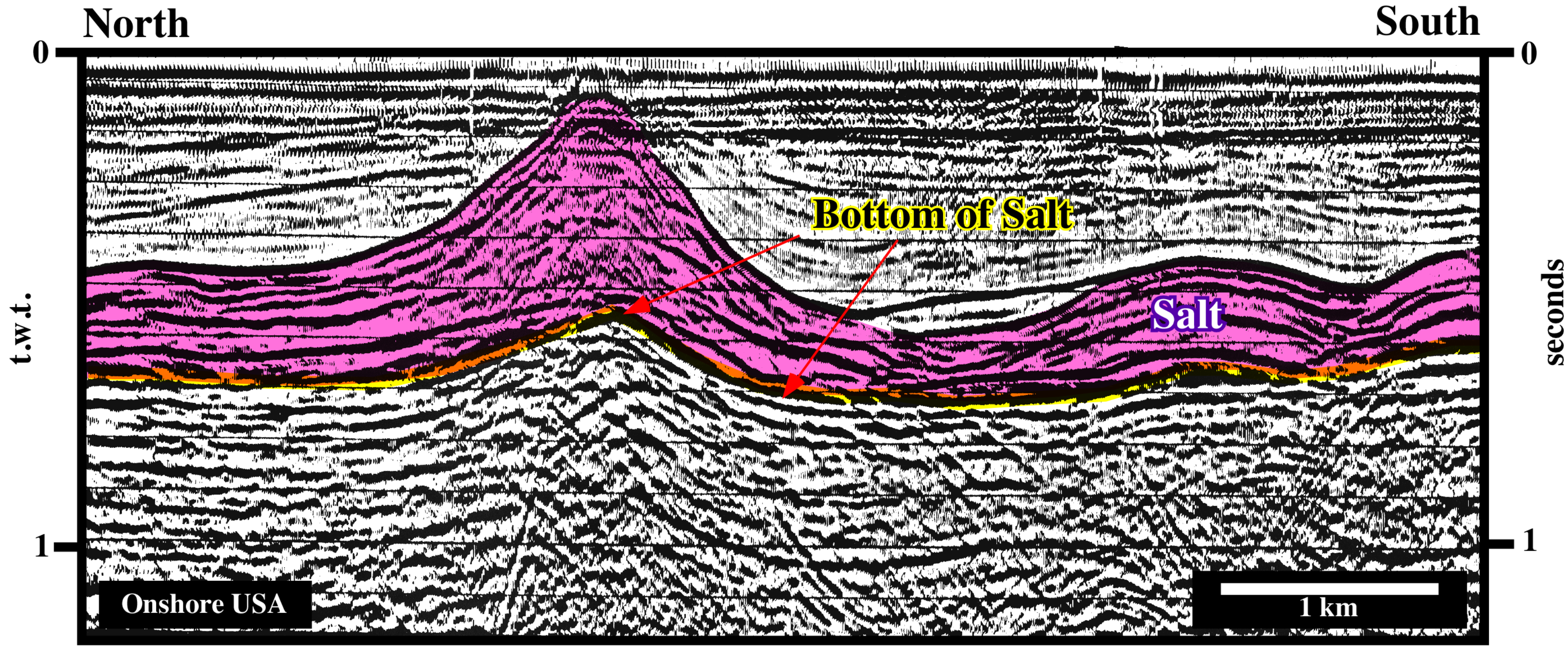


Fig. 108- This seismic line from onshore Louisiana illustrates a seismic artifact induced by an evaporitic interval. The bottom of the salt layer is pulled-up where the salt interval is thicker.

The above seismic comes from an evaporitic basin where lateral changes in salt thickness are frequent. These thickness changes induce lateral changes in the velocity interval, which cause obvious seismic artifacts. However, without a corrected time-depth conversion, it is sometimes dangerous to assume, *a priori*, a flat salt bottom. Indeed, it has been shown, for instance in offshore Angola, that salt steps are often observed in association with major fracture zones.

F.6- Reefs

The development of reefs or organic build-ups in which the seismic waves often have a high velocity, induce important pull-ups of the horizons associated with their bottoms, as is sketch in fig. 109. Nevertheless, generally, on the ground, hence, in geological models, reefs have bottoms showing planar geometries. A seismic line of such a reef is sketched below.

Reefs

6.1) Geological Model

6.2) Seismic Line

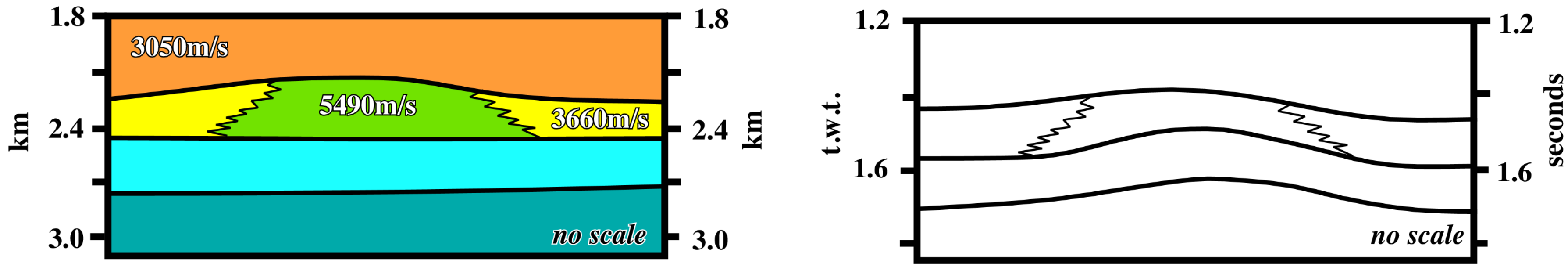
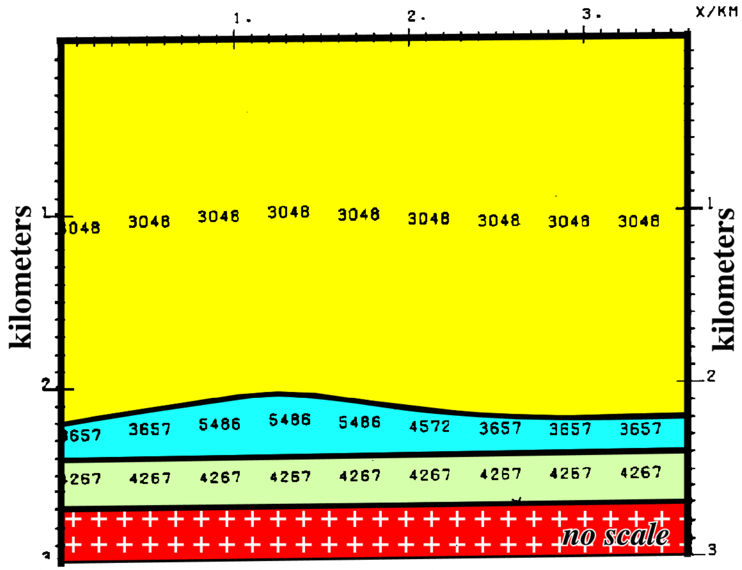


Fig. 109- On this reef geological model, above a planar limestone sole (light blue), a reef with a compressional wave velocity of 5490 m/s, is laterally bounded by shaly sediments (yellow) with a much lower velocity (3660 m/s), which are overlain by even slower sediments (brown interval, 3050 m/s). The seismic answer of such a model is roughly depicted on the right. The horizon associated with the bottom of the reef shows a significant pull-up.

This geometry, with a pull-up of the bottom of the reef, is normal when the reef is developed adjacent to a low velocity interval such as shale. However, if a porous reef is developed within a tight calcareous environment, the geometry of the bottom of the reef is inverted, that is to say, the associated marker, if there is a marker, is pulled-down. Actually, in certain basins, for instance in the Michigan basin (USA), the recognition of reefal anomalies is mainly based in the absence of reflector. In other words, when, in a continuous and high amplitude marker, emphasizing a limestone interval, an abrupt interruption of the reflector occurs during few kilometers, it may be due to the presence of a local porous reef.

Reefs

6.3) Mathematical Model



6.4) Seismic Response

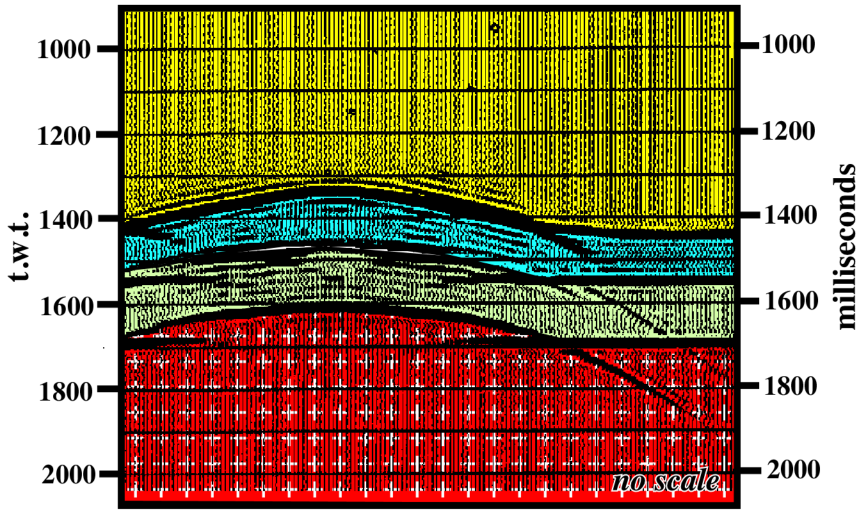


Fig. 110- Notice that in the geological model the compressional wave velocity, in the blue interval (limestone with a local reefal development) changes significantly. It is much higher (around 5500 m/s) in the reef than in the surrounding sediments. Such a reef is supposed to be tight. The seismic response of such a model, on the right part of the figure shows that not only the bottom of the reef, but all others markers below are pulled-up.

The pull-up of the bottom of the reef is very sharp, as is the time thickness interval of limestone facies, which is clearly thicker in the velocity model. As said previously (Ashstart field, in offshore Tunisia, page 86-91) this kind of seismic artifact occurs very often near the platform limit-upper slope, where shelf margin reefs build-up, particularly in regressive stratigraphic intervals. The next figure (fig. 111) illustrates an instance taken from offshore Indonesia.

Seismic Artifact
induced by a
Reef

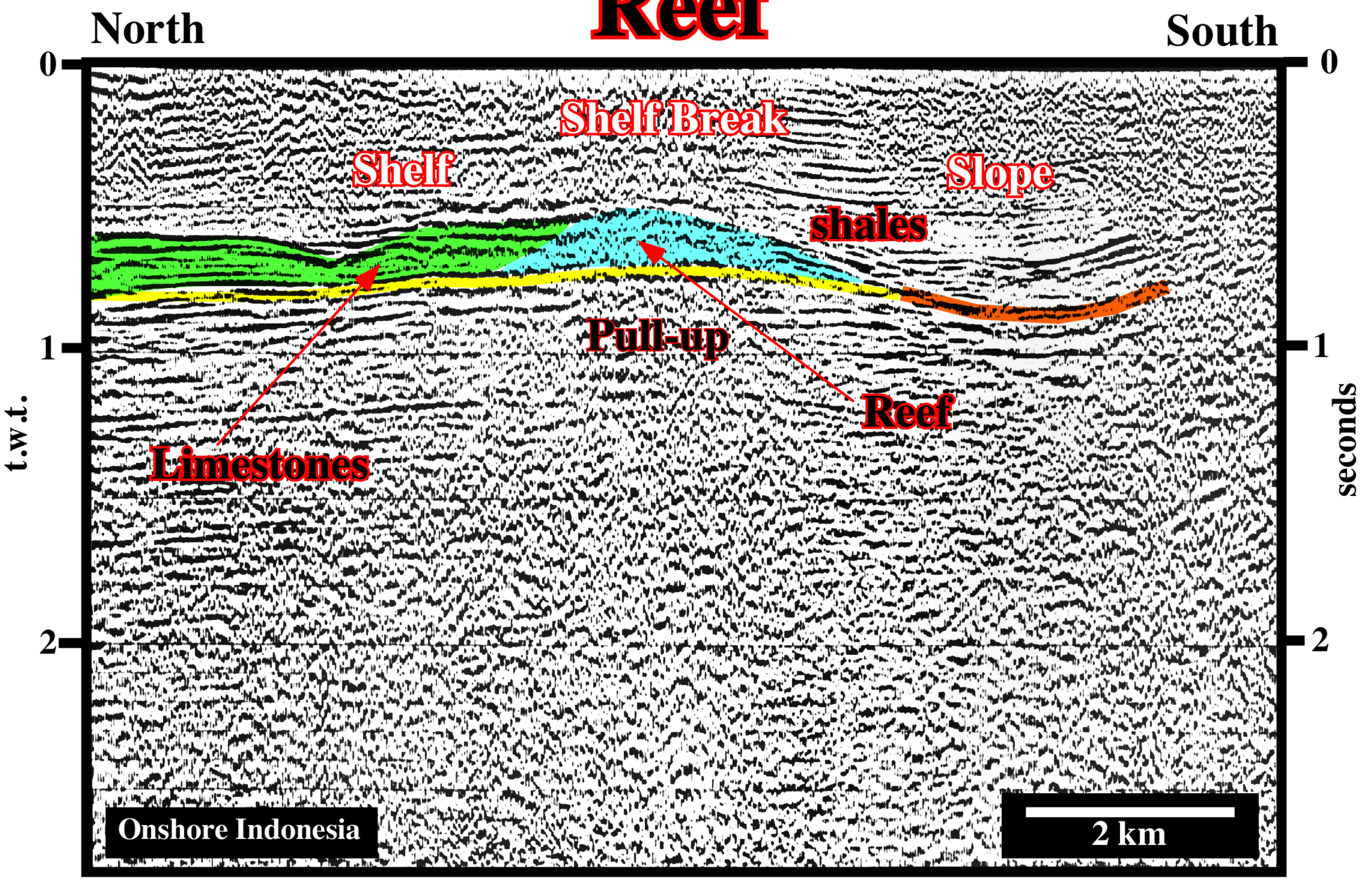


Fig. 111- On this seismic line, from offshore Indonesia, the shelf break of the upper colored interval seems to emphasize the development of a reef. Actually, the bottom of the shelf limestone is pulled-up. This pull-up is enhanced by the pull-down of the reflectors associated with the slope shales (in brown).

F.7- Canyons

Submarine canyons, when not filled-up by sediments, induce important lateral velocity changes due to different properties of water and sediments. Fig. 112 shows the pull-down anomaly of the reflections underlying the bottom of the submarine canyon. The geological depth interpretation is illustrated in the lower part of the figure and the more likely seismic response (un-migrated line) on the right part.

Canyons

7.1) Geological Model

7.2) Seismic Line

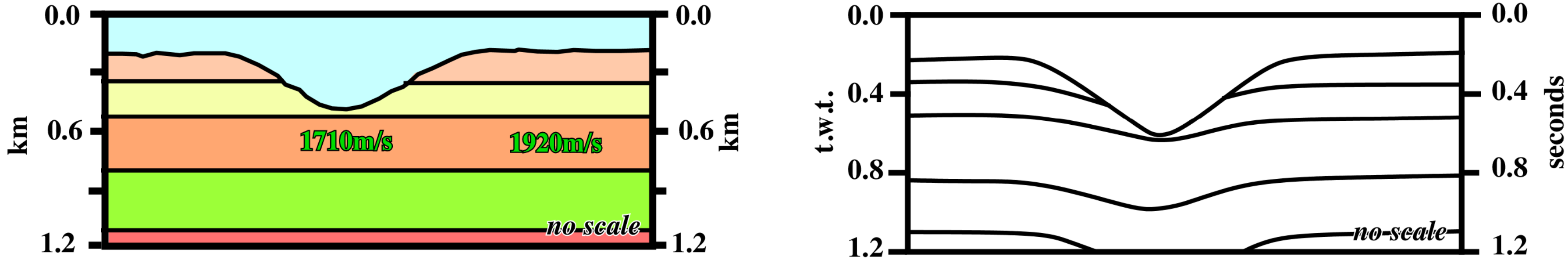
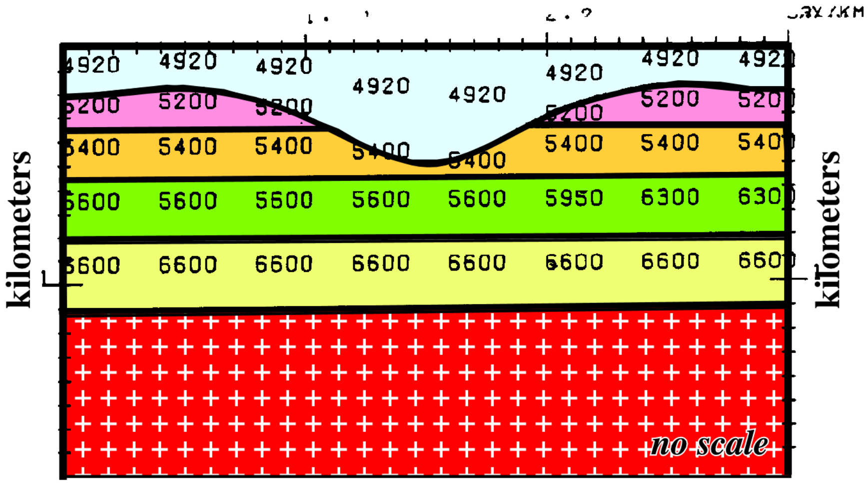


Fig. 112- Canyons (submarine valleys) when unfilled by deep water sediments, induce obvious seismic artiftacts. In fact, they create sharp lateral changes in the compressional wave velocities (water versus sediments). On a seismic line, when the markers directly below a submarine valley show a synform geometry, the most likely hypothesis is that such a geometry is induced by the lateral velocity change between the water and sediments. Note, the term canyon is often misleading. In Geology, a channel is a linear current mark, larger than a groove, produced on a sedimentary surface parallel to the current, and is often preserved as a channel cast. However, very often, petroleum geologists use the term channel to express its sedimentary filling. Indeed, and particularly, in deep offshore Angola, the filling of turbidite submarine valleys are the most likely prolific reservoir-rocks, explorationists have a tendency to name turbidite channels the onlap filling of the submarine valleys. In fact, the infilling of a submarine valley does not follow the basic principles of the infilling of distributary valleys. The filling of submarine valleys largely postdate the erosional events. On the other hand, the filling corresponds to the stacking of instantaneous but quite time-spaced geological events, i.e. gravity currents.

The velocity model and the seismic response of a geological model, in which a submarine canyon erodes the surrounding sediments is illustrated below. The seismic response is also illustrated below (fig. 113). It was determined using the wave equations software.

Canyons

7.3) Mathematical Model



7.4) Seismic Response

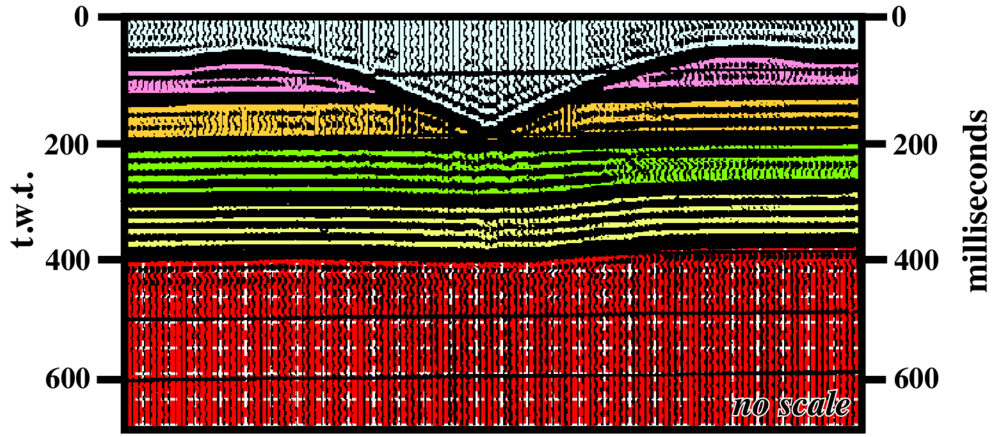


Fig. 113- In the velocity model, illustrated above (left part of the figure), there is no lateral changes in the compressional wave velocity. Only the concave geometry of the submarine valley induces local velocity changes, which on the seismic response are respresented by the slight pull-down of the seismic reflector underlying the submarine channel. However, as depicted on the seismic line illustrated on fig. 114, the seismic is not so obvious as above, since real undulating seismic reflectors can be pictured, on a time-profile (un-migrated or migrated) as horizontal (see fig. 114).

Seismic Artifact
induced by a
Submarine Valley

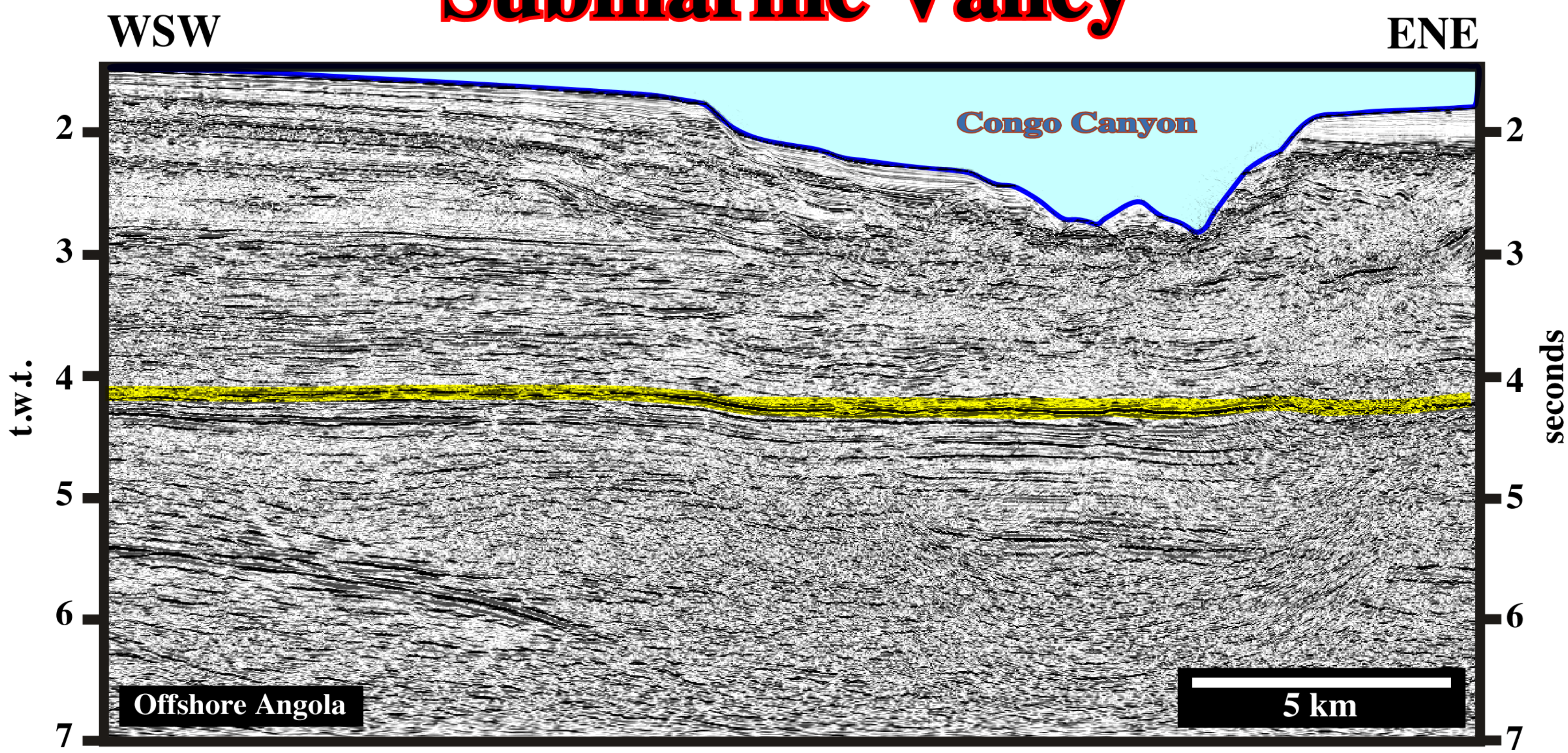


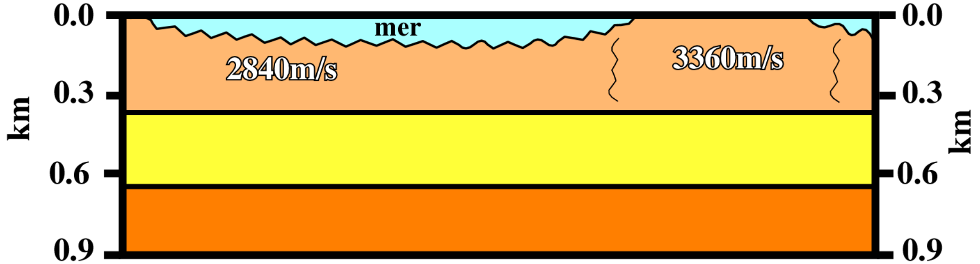
Fig. 114- On this seismic line, from the deep offshore Angola, a typical seismic artifact, induced by the lateral change in water depth created by the Congo Canyon (in blue), is illustrated by the horizontal geometry of the yellow marker. Actually, the horizontal geometry of this marker is apparent. Theoretically, the change in water-depth, induced by the Congo Canyon, delays, locally, the seismic waves, hence, all seismic markers below it are pulled-down. However, as the yellow marker is horizontal, that means, in reality, as in a depth-converted line, it is concave upward, since the delay of the seismic waves is correct. In fact, the yellow marker corresponds to the top of an inverted rift-type basin. Subsequently, a potential structural trap, at the level of the rift-type basin, exists under the canyon.

F.7- Freezing areas

In very cold areas, as in North Slope (Canada), it is very common to see a quite misleading seismic artifact, often interpreted as compressional tectonic feature, as it is illustrated in fig. 115. The antiform geometry of the reflectors is induced bythe higher velocity of the seismic waves through the sub-cropping freezing porous sediments, as depicted bellow.

Freezing Areas

8.1) Geological Model



8.2) Seismic Line

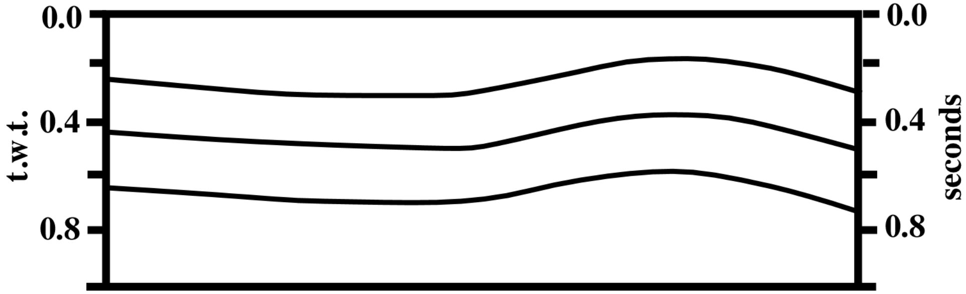
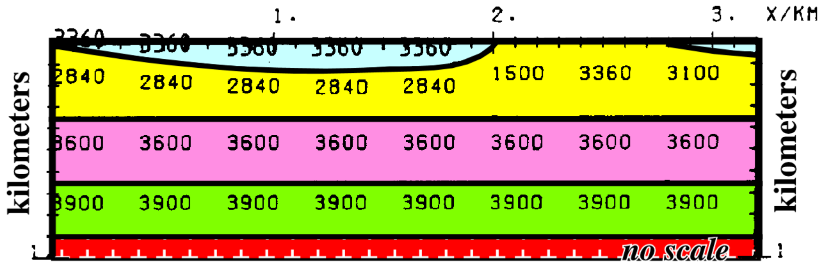


Fig. 115- This figure illustrates a typical seismic artifact found very often in permafrost areas, that is to say, in any soil, subsoil, or other surficial deposits, or even bedrock, occurring in arctic, subarctic, and alpine regions, at a variable depth beneath the Earth's surface, in which a temperature below freezing has existed continuously for a long time. Indeed, in the areas with a freezing temperature, the compressional wave velocity is substantially increased and so, in a seismic response, the associated reflectors will be pulled-up as illustrated above. In the geological model, the change in the compressional wave velocity from 2840 m/s to 3360 m/s is due to the fact that water filling the pores in outcropping sediments is frozen. In fact, the thickness of the permafrost can range from over 1000 m in north to 30 cm in the south. Indeed, it underlies about one-fifth of the world's land area.

Freezing Areas

8.3) Mathematical Model



8.4) Seismic Response

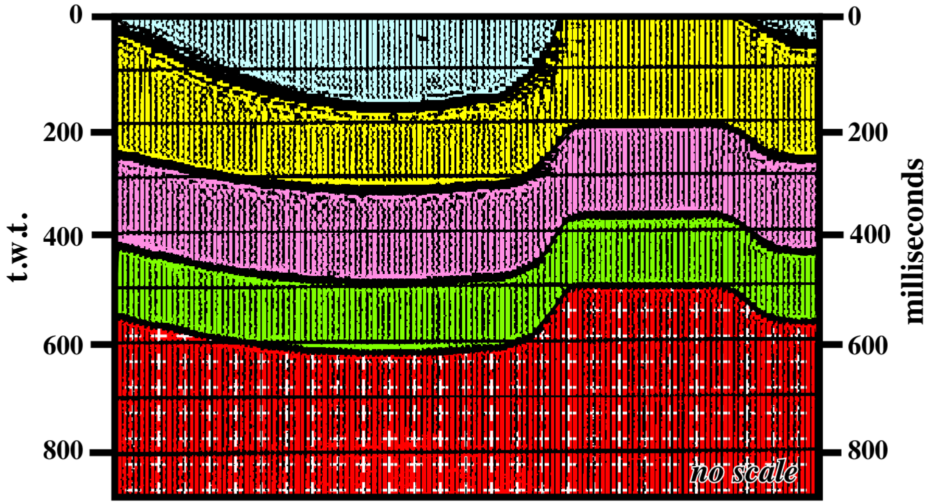


Fig. 116- The seismic response of a geological model with freezing areas is more than evident. Actually, this particular seismic artifact is easily recognized by seismic interpreters having a minimum of tectonic knowledge. Indeed, theoretically speaking, a concentric fold (the thickness of strata is constant, when measured perpendicular to the bedding planes) cannot keep the same geometry in depth, since volume problems (Goguel's law) increase with depth. In other words, when an interpreter recognizes on a seismic line an antiform structure that keeps the same shape in depth, they must suspect a seismic artifact, particularly if the seismic line comes from an area where permafrost is possible.

F.9- Synclines

In order to understand the seismic response of synforms with different geometries we will show several velocity models and their associated responses.

Synforms

9.1- Geological Model

9.2- Seismic Response

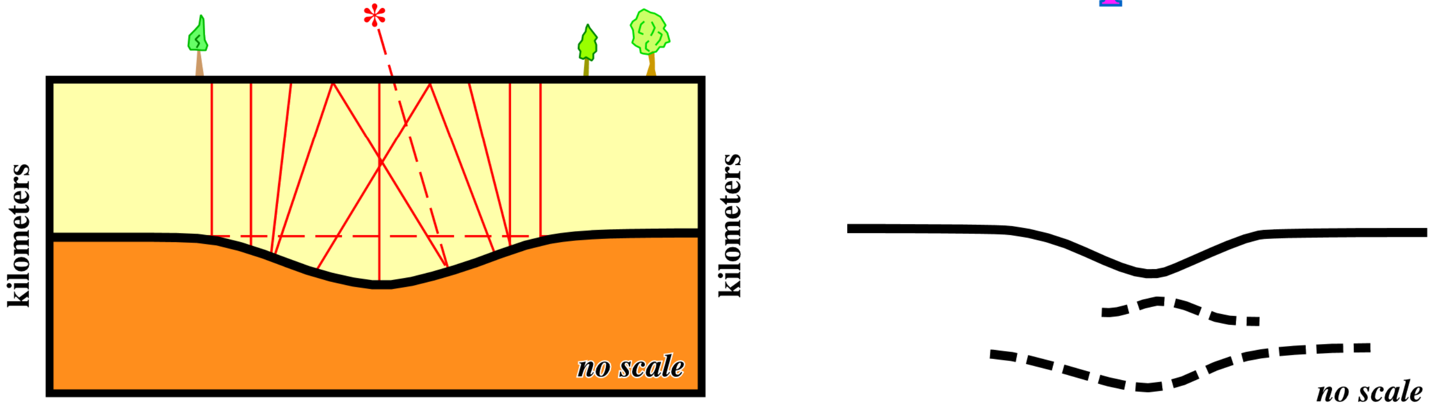
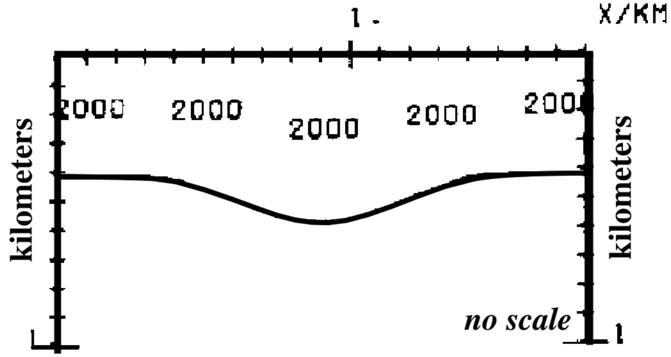


Fig. 117- On this figure a geological model of a synform and its seismic response on an unmigrated seismic line is illustrated. Notice the geometry of the synform (assuming the synform corresponds to an arc of circle) suggests a potential circle centre above the ground.

Synforms

9.3) Mathematical Model



9.4) Seismic Response

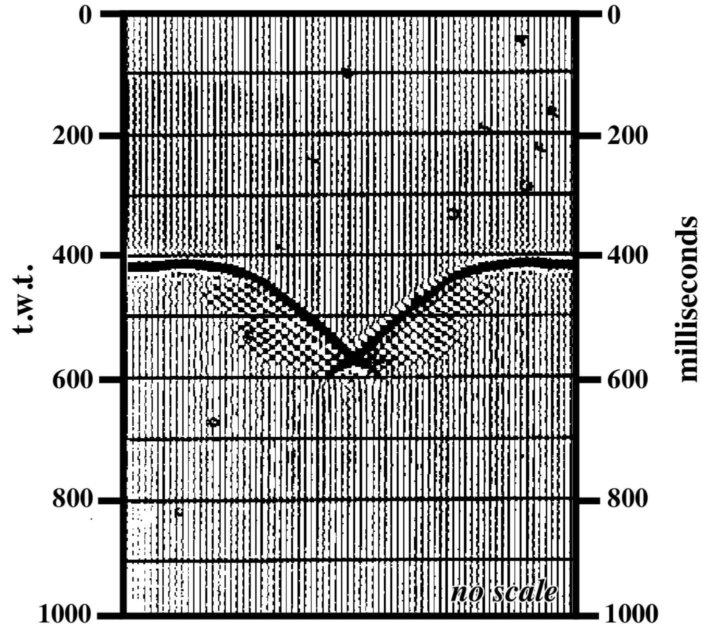
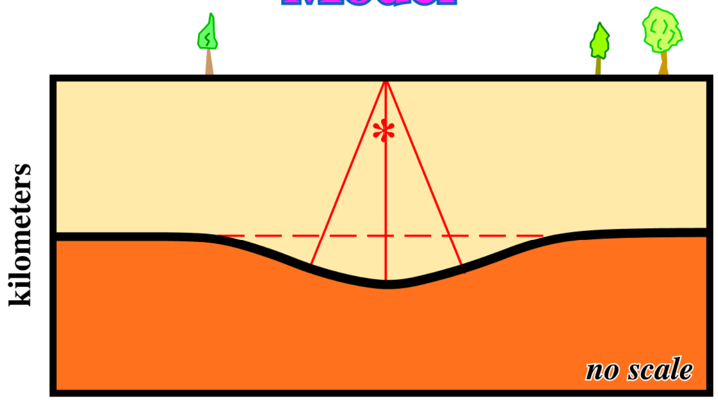


Fig. 118- In the mathematical model of the previous geological model (circle centre of synform above the ground) the seismic velocity of the upper interval was assumed to be 2000 m/s. On the seismic answer (unmigrated) the synform marker almost does not have any “moustache”.

Synforms

9a.1- Geological Model



9a.2- Seismic Response

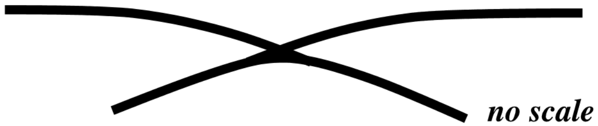
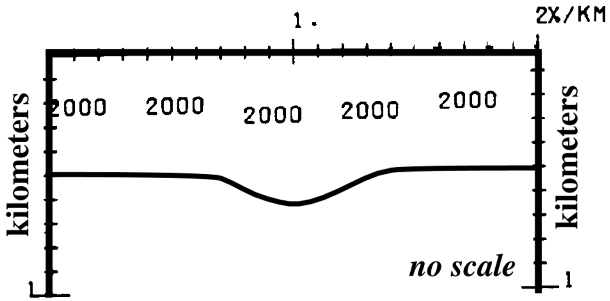


Fig. 119- On this geological model, the center of the synform is below the Earth's surface, near the top of the upper sedimentary package. Contrariwise of the previous seismic answer, in this case, the reflector associated with the synform interface shows a quite sharp and large "moustache".

Synforms

9a.3) Mathematical Model



9a.4) Seismic Response

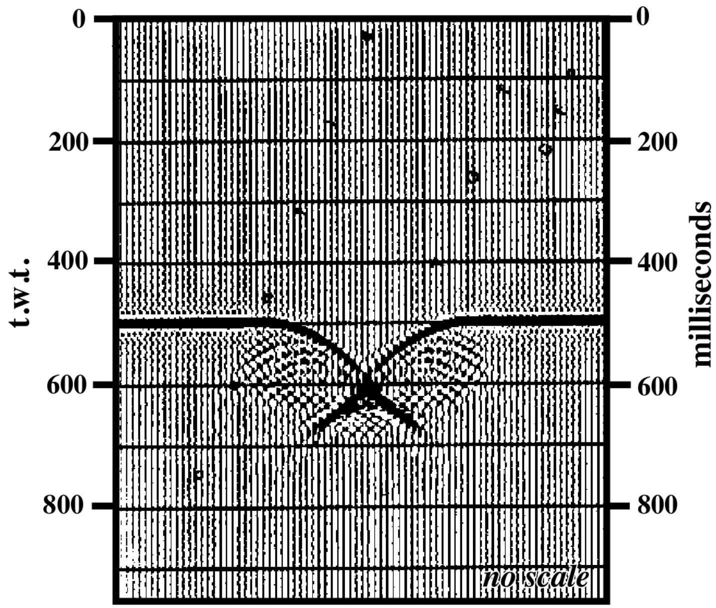


Fig. 120- In relation to the previous mathematical model only the curvature of the synform was changed. In this particular instance the curvature center is under the Earth's surface. The seismic response of the synform interface, on an unmigrated line, strongly suggest a significant “moustache”.

Synforms

9a.1- Geological Model

9a.2- Seismic Response

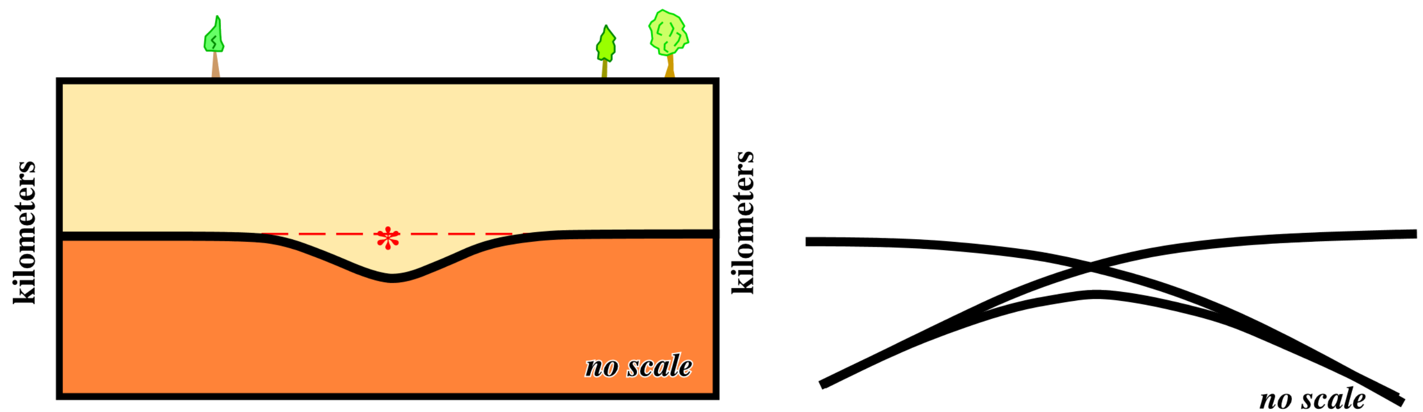
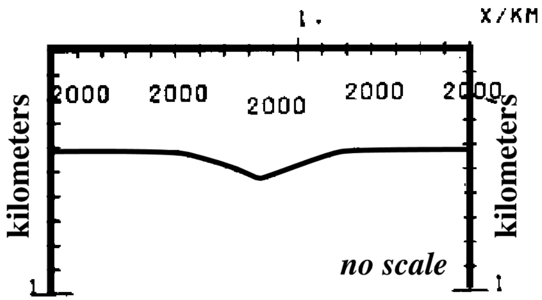


Fig. 121- In this geological model, the curvature centre of the synform is under the Earth's surface, near the bottom of the upper sedimentary interval, that is to say deeper than in the previous example. The potential seismic answerof the synform interface, as expected, corresponds to a butterfly geometry (large "moustaches").

Synforms

9b.3) Mathematical Model



9b.4) Seismic Response

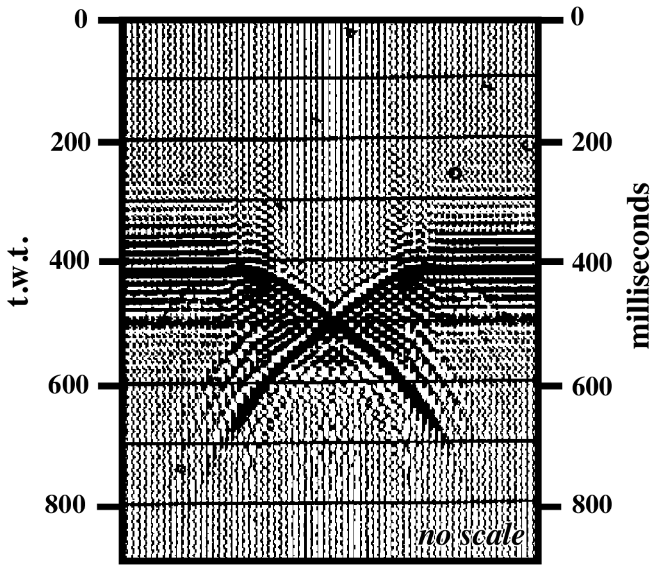
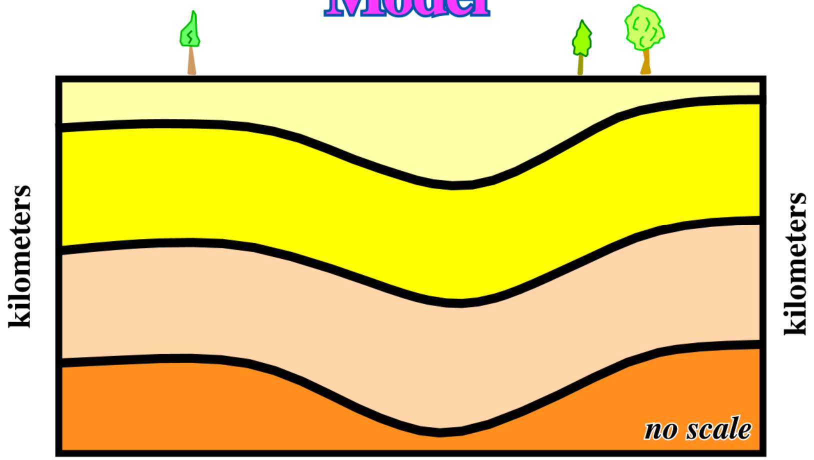


Fig. 122- The seismic response to the mathematical model corroborates the previous predicted seismic answer. Indeed, the butterfly geometry is quite easily recognized on the above unmigrated seismic answer.

Synforms

9c.1) Geological Model



9c.2) Seismic Response

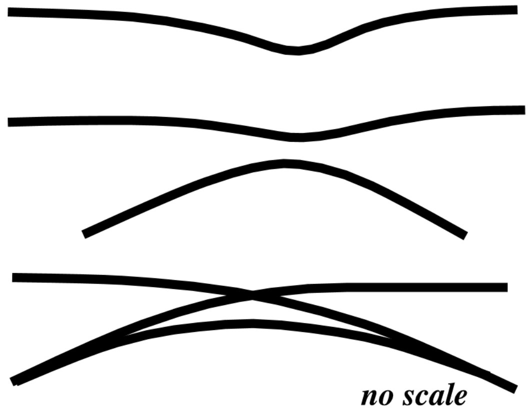
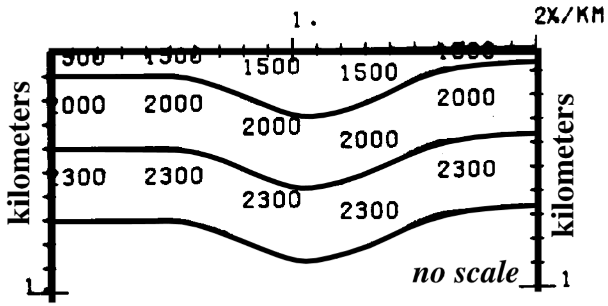


Fig. 123- Finally, on this geological model, from bottom to top, there are three major synforms with decreasing curvatures, that is to say, the curvature center of the upper synform is located above the Earth's surface, while the other are deeper in the ground. The likely seismic answer is, from top to bottom, a synform geometry without "moustaches", with moustaches and with a butterfly geometry.

Synforms

9c. 3) Mathematical Model



9c. 4) Seismic Response

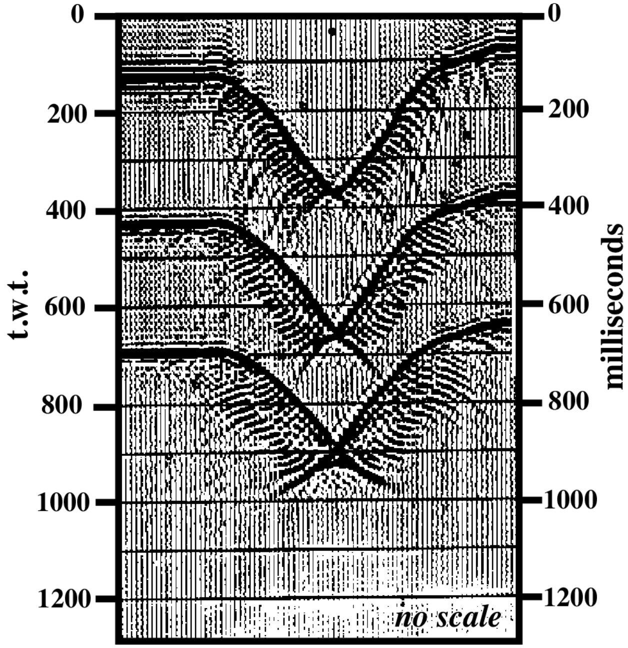


Fig. 124- In the mathematical model the sedimentary intervals have average velocities of 1500, 2000 and 2300 meters per second and decreasing curvatures. The unmigrated seismic response corresponds to the stacking of three synform reflectors. However, from top to bottom, they have different geometries: (i) without “moustaches”, (ii) with “moustaches” and (iii) butterfly like.