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DETAILED GEOLOGIC INFORMATION FROM SEISMIC DATA[1]

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ABSTRACT

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Seismic data provide an invaluable amount of information on the subsurface geology, particularly because of its dense lateral sampling. However, on the spatial resolution properties there is still a lot to be desired. In this paper the principles of seismic resolution are discussed and limitations in practical situations are indicated.

INTRODUCTION

One of the attractive properties of seismic information is its dense spatial sampling. Nowadays lateral prediction of subsurface properties, generally starting at one or more existing wells, is unthinkable without seismic data.

Unfortunately, the relatively low frequency content of seismic data imposes an important limitation on the resolving power of the seismic method. Although many succesful attempts have been undertaken to enhance the high seismic frequencies, current seismic data still lacks sufficient resolution for a detailed subsurface study.

Two recent developments appear to be very promising for the extraction of high resolution information from seismic data:

1. Interpretive seismic migration, using a global geologically-oriented depth model as a starting subsurface model;
2. Interpretive seismic trace inversion, using the interpreter's detailed interpretation of the zone of interest as an initial model.

For both procedures the specification of extra nonseismic information is essential and use of fast interactive hardware is required.

In this paper a user-oriented explanation of seismic inversion is given. A discussion is devoted to the potentially high resolving power of interpretive inversion techniques. Developments that may be expected in the near future will be indicated.

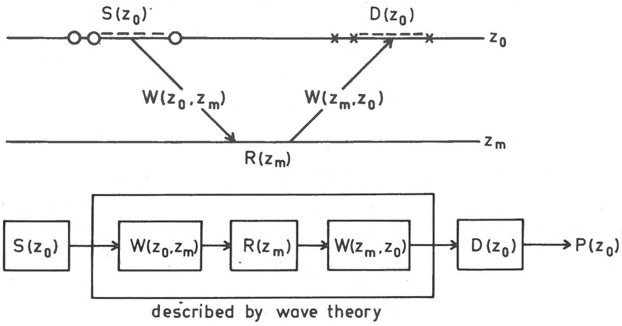

Fig. 1
Propagation and reflection of seismic waves.
1. Downward propagation:

$$S(z_m) = W(z_m,z_o)S(z_o), \qquad m = 1,2,3,\ldots,M$$

where $S(z_o)$ represents the seismic source wave field at the surface z_o, $W(z_m,z_o)$ describes how the seismic wave field propagates from the surface z_o to depth level z_m and $S(z_m)$ respresents the downward travelling source wave field at depth level z_m.

2. Reflection:

$$P(z_m) = R(z_m)S(z_m), \qquad m = 1,2,3,\ldots,M$$

where R describes how the downward travelling source wave field is transformed into an upward travelling reflected wave field.

3. Upward propagation:

$$P(z_o) = \sum_{m=1}^{M} W(z_o,z_m)P(z_m),$$

where $W(z_o,z_m)$ describes how the reflected wave field propagates from depth level z_m to the surface z_o and $P(z_o)$ represents the sum of the reflected wave fields from all depth levels (z_1, z_2, ... z_M) at the surface z_o.

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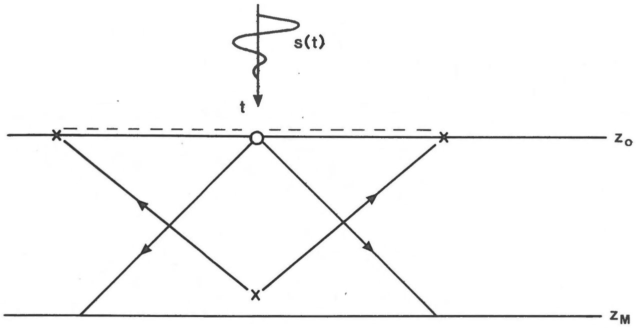

Fig. 2a
Seismic beams: illumination by one point source and reflection from one point inhomogeneity.

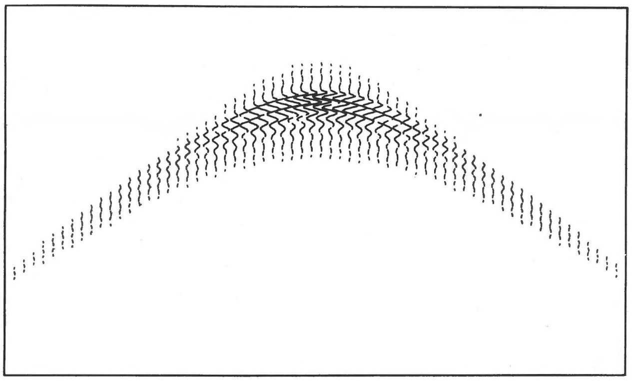

Fig. 2b
Response of one point inhomogeneity.

THEORETICAL ASPECTS

Fig. 1 shows how a seismic wave, generated by one or more sources at the surface, propagates into the subsurface, reflects at inhomogeneities and propagates back to the surface where it is measured by a sequence of detectors.

Propagation operator $W(z_m,z_o)$ quantifies how depth levels z_m are illuminated by a given source at the surface z_o. It shows that in practical situations illumination does not occur by a narrow beam: one source point illuminates a large subsurface volume. All inhomogeneities in this volume act as new secondary sources. Propagation operator $W(z_o,z_m)$ quantifies how each secondary source at depth level Z_m illuminates the surface z_o. This principle is shown in Fig. 2: one point source illuminates a large volume in the subsurface and one point inhomogeneity in this volume illuminates a large area at the surface.

Seismic inversion aims at modifying propagation operators $W(z_m,z_o)$ and $W(z_o,z_m)$ such that very narrow beams are simulated for downward and upward propagation. In addition, seismic source wavelet s(t) is transformed as well as possible into an impulse.

Fig. 3a shows the response of a number of point inhomogeneities. Note the complicated interference pattern. After seismic inversion the individual point inhomogeneities can be easily recognized (Fig. 3b). With reference to this

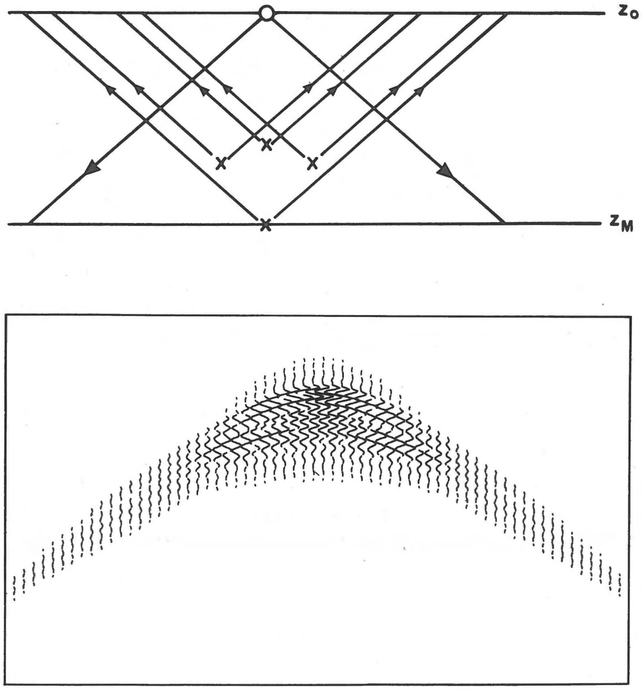

Fig. 3a
Illumination and response of four point inhomogeneities.

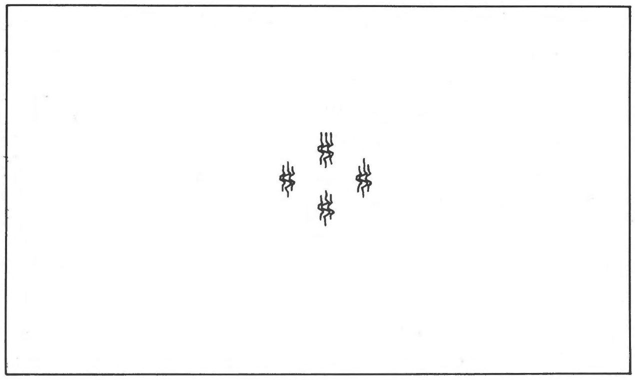

Fig. 3b
The response of four point inhomogeneities after seismic inversion.

inversion result, vertical resolution describes how well vertically displaced inhomogeneities can be visually perceived as separate images. Similarly, lateral resolution describes how well laterally displaced inhomogeneities can be visually perceived as separate images.

IMPROVEMENT OF VERTICAL RESOLUTION ("TRACE INVERSION")

Seismic deconvolution is one part of the seismic inversion process which aims at improving the vertical resolution by decreasing the length of seismic wavelet s(t).

Fig. 4a shows an example of a seismic wavelet with its frequency spectrum. At the frequencies f_L and f_h the signal-to-

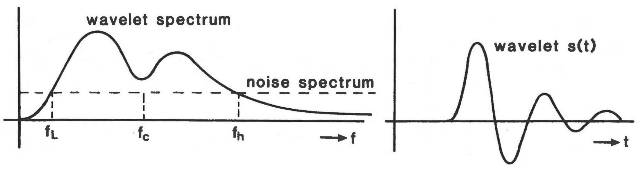

Fig. 4a
Seismic wavelet with spectral information.

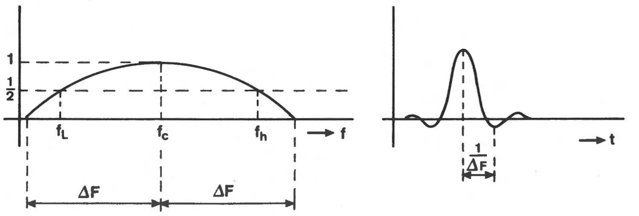

Fig. 4b
Seismic wavelet (in terms of its envelope) with spectral information after optimum deconvolution.

noise ratio equals unity. In seismic deconvolution the frequency range ($f_L \rightarrow f_h$) is availlable only (temporal bandwidth). Outside this range the noise is stronger than the signal and, therefore, suppression should occur. Fig. 4b shows the optimum cosine-shaped frequency spectrum with the related deconvolved wavelet. The distance between main lobe maximum and first side lobe minimum is given by $1/\triangle F$. If we use this quantity as a measure for vertical resolution then for different frequency ranges the separative power in depth can be computed. For example, using a velocity of 2500 m/s:

Table I

f_L in Hz	f_h in Hz	$\triangle F$ in Hz	$\triangle T$ in ms	$\triangle z$ in m
10	30	10	100	125
10	40	15	67	83
10	50	20	50	63
10	60	25	40	50
10	70	30	33	41
15	95	40	25	31

From the above it follows that vertical resolution is directly related to temporal bandwidth (f_h-f_L) and, therefore, in practical seismic situations vertical resolution of optimally deconvolved data is given by ca. 40 m for shallow data and ca. 120 m for deep data.

Seismic deconvolution does not require any specific information from the reflectivity of the subsurface. Basically, seismic wavelet s(t) should be known and spectral properties of the noise should be given. However, a new development in seismic inversion shows that if also specific information is given on the reflectivity of the subsurface the vertical resolution can be significantly improved. Generally these trace inversion techniques are referred to as "parametric inversion", the parameters being reflection coefficients and travel times. In the near future one may expect that in reservoir stratigraphy parametric inversion of seismic data will play an invaluable role in two different ways:

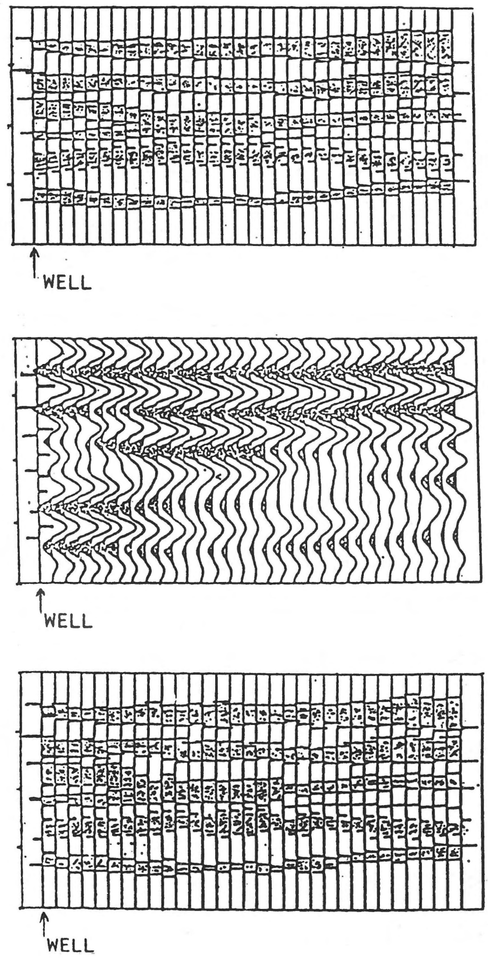

Fig. 5
Comparison between deconvolution and parametric inversion. Top: true reflectivity; middle: deconvolved data; bottom: result of parametric inversion.

1. High resolution seismic trace inversion beyond the seismic bandwidth
2. Quantitative verification of a seismic-geologic model resulting from seismic interpretation.

Fig. 5 illustrates the principle.

IMPROVEMENT OF LATERAL RESOLUTION ("MIGRATION")

In the foregoing we have seen that inversion for seismic time wavelet s(t) is one part of the seismic inversion process. The other part is inversion for propagation operators W such that narrow vertical "beams" are simulated. The width of these narrow beams determine the lateral resolution after inversion.

In seismic techniques the simulation of narrow beams is achieved in the computer by the migration process. It may be considered as a synthetic double focussing process as illus-

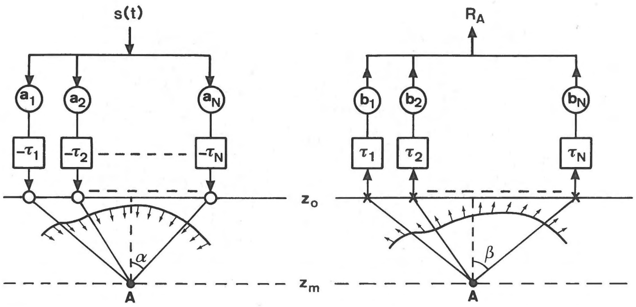

Fig. 6
Migration may be considered as a synthetic double focussing process for each subsurface point by combining in the computer the data from different shots (focussing at illumination) and combining the data from different detectors (focussing at reception).

trated in Fig. 6. By choosing the amplitudes of the different source and detector contributions correctly, a true-amplitude high-resolution estimate of the reflectivity in subsurface point A is obtained.

The width of the simulated vertical beams at focussing point A is determined by

a. The aperture angles α and β (shot range and detector range used during migration)
b. The central frequency f_c of the seismic wavelet (size of shot and detector ranges in terms of wave length).

The larger α and β, and the larger f_c, the smaller the beamwidth will become at the focuss point and, therefore, the better the lateral resolution. Note that for $f_c \rightarrow \infty$ an unlimited high lateral resolution can be achieved, even for limited α and β values ("pencil beams"). This property is used in acoustic microscopy.

Fig. 7 shows the response of three point inhomogeneities before and after seismic inversion (deconvolution and migration), using for α and β the values 60°, 40° and 20°. Note the significant lateral smearing for low values of α and β.

A handy rule of thumb for lateral resolution is given by (Fig. 8)

$$\Delta L = \frac{\lambda_c}{2L} z, \qquad z > L$$

where $\tan \alpha = \tan \beta = L/z$. In addition ΔL is never smaller than the pattern length used in the field.

Seismic migration needs as input a global model. Sofar, this depth model is generally specified in terms of a migration-velocity distribution as a function of seismic time. However, there is a clear trend towards specifying a more geologic-oriented depth model in terms of a number of main geologic units with their seismic properties. After migration this model is verified with the migrated data wich may result in an update of the global depth model ("interpretive migration").

CONCLUSIONS AND FUTURE DEVELOPMENTS

We have indicated that resolution depends on frequency content and available information. For high vertical resolution the following properties are required:

1. Seismic reflection with a large bandwidth (f_h-f_L), of which the frequency components have an amplitude above the noise level ("deconvolution")
2. A seismic time wavelet that is accurately known
3. An initial estimate of the reflectivity function ("parametric inversion").

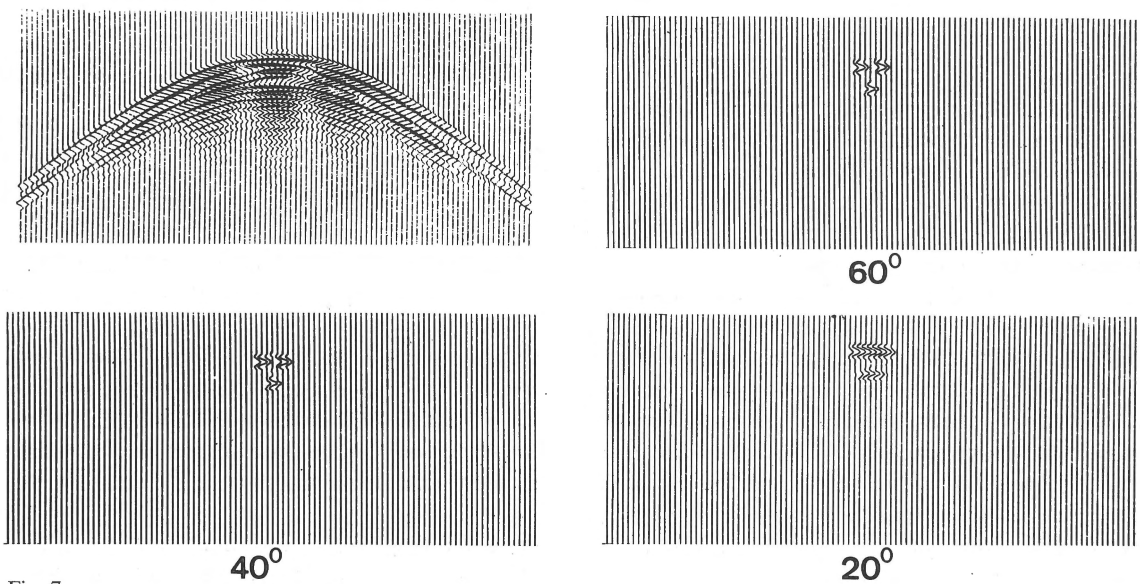

Fig. 7
Influence of the aperture angles α and β on migration; f_c = 25 Hz.

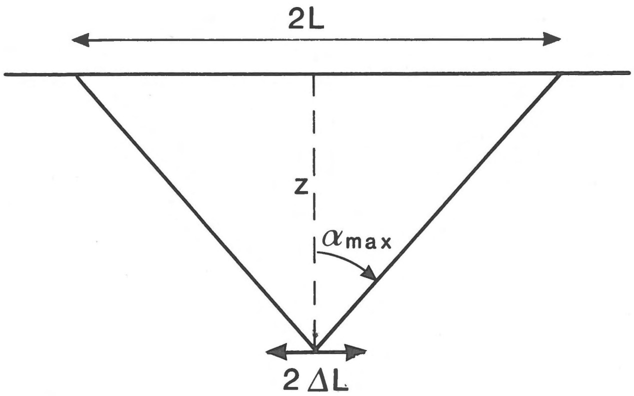

Fig. 8
If the migration operator uses a data window 2L then the lateral resolution at depth level z is given by $\triangle L = (\lambda_c/2L)z$.
(λ_c, is the wavelength related to the central seismic frequency).

It was argued that the future trend in high-resolution trace inversion is given by parametric inversion techniques.

Similarly, for high lateral resolution the following properties are required:

1. Large central frequency (f_c), meaning that high frequencies are essential
2. Large aperture angles α and β, meaning that many traces should be included during migration
3. The use of small patterns in the field
4. An accurate estimate of a global geologic-oriented seismic depth model ("interpretive migration").

We may expect that in the near future pre-stack migration techniques will gradually take over current "stacking" and "post-stack migration" processes.

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