Part 1

Delphi: Delft philosophy on acoustic and elastic inversion

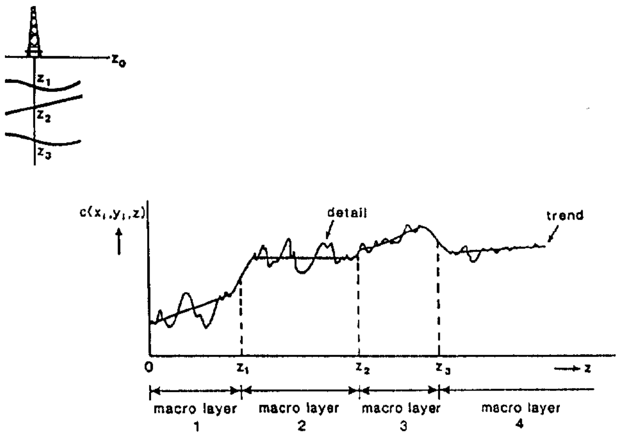
By A.J. BERKHOUT and C.P.A. WAPENAAR
Laboratory of Seismics and Acoustics
Delft University of Technology
The Netherlands

Delphi is the integration of the Delft migration consortium Triton and the Delft stratigraphic inversion consortium Princeps, both of which are assigned to the university's Laboratory of Seismics and Acoustics. The goal of this combination is transformation of shot records to rock and pore parameters via a stepwise integrated inversion approach. In 1988 this research was sponsored by 22 companies.

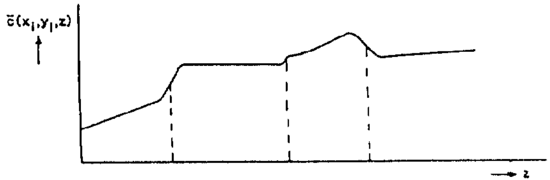
In conventional seismic processing techniques, the seismic wave fields measured at the surface are processed in the time domain (deconvolution, CMP stacking, time migration). Therefore, conventional seismic processing may be referred to as time-oriented. In the modern view of seismic processing, it is realized that accurate information (structural, stratigraphic, lithologic) on the subsurface can only be obtained if the wave fields—measured at the surface—are downward extrapolated to the subsurface grid points (depth points) of interest. Therefore, modern seismic processing may be referred to as depth-oriented. It may be stated that the conventional time domain approach provides an economic preview of the subsurface. However, if at selected areas a more accurate image is required, then a depth-point oriented approach is a prerequisite. Three-dimensional, depth-point oriented elastic seismic processing is the subject of the Delphi consortium, and this paper is a brief outline of its strategy and methods.

I. Theoretical background

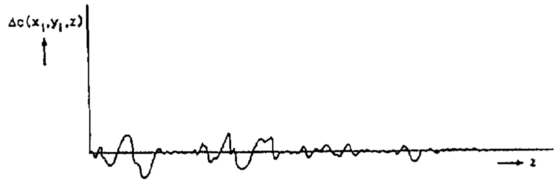
Description of the subsurface. Figure 1a is a typical velocity profile obtained from well measurements. An interesting and important analysis of the measurement curve (velocity log) is given by subdivision into trend and detail. The trend (Figure 1b) gives information on the depth-dependent compaction properties of the subsurface. The detail (Figure 1c) gives information on the different rock and pore properties of the individual geologic layers (within the resolution of the velocity log). Using trend informa-



1a. TOTAL



1b. TREND



1c. DETAIL

Figure 1. Description of the subsurface in terms of trend and detail.

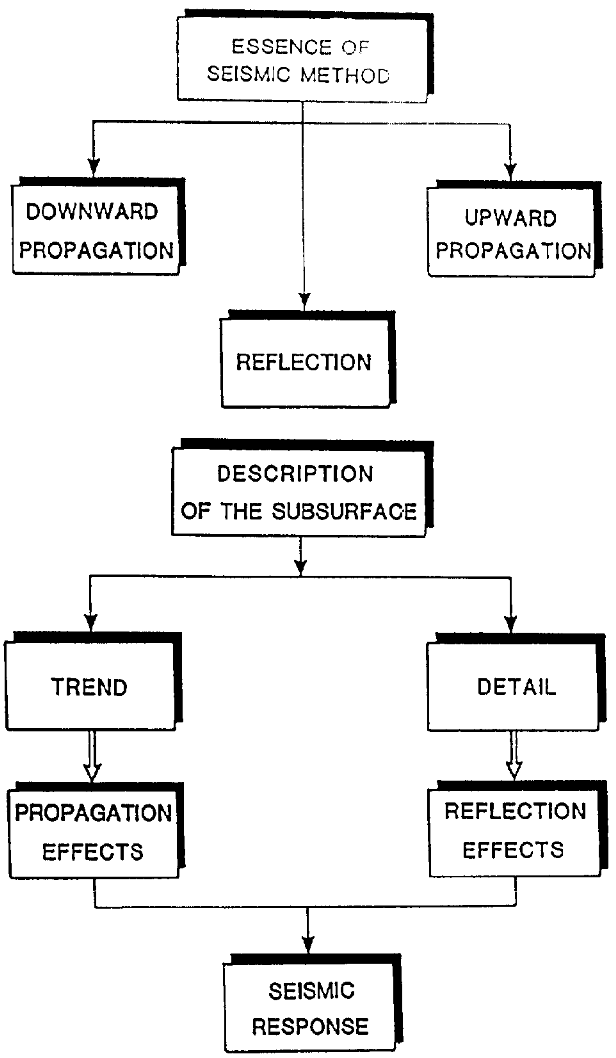


Figure 2. (a) Seismic responses are defined by the propagation and reflection properties of the subsurface. (b) The macro and fine layering in the subsurface determine the propagation and reflection effects in the seismic response.

tion, the subsurface may be subdivided into so-called macro layers, where each macro layer can be seen as a package of geologically related layers with the same compaction property. The distinction between trend and detail, or macro layering and fine layering, should play a key role in seismic inversion.

The essence of the seismic method is given by propagation and reflection (Figure 2a). The source wave field propagates down in the subsurface, reflects at the layer boundaries and the reflected wave fields propagate back to the surface. Hence, the seismic response we measure at the surface represents a mixture of propagation and reflection information. The major part of seismic processing is dedicated to the elimination of propagation effects from the seismic response, yielding a correctly positioned true amplitude reflectivity image. Referring back to the description of the subsurface cited above, we may make the important statement (graphically presented in Figure 2b) that propagation is largely determined by the trend of the subsurface (macro layering) and reflection is largely determined by the detail of the subsurface (fine layering). As a consequence, for the elimination of propagation effects, the macro model of the subsurface should be available. Or, in other words, seismic processing should be based on macro subsurface models. This means that estimation of macro models should be a key issue in the seismic industry.

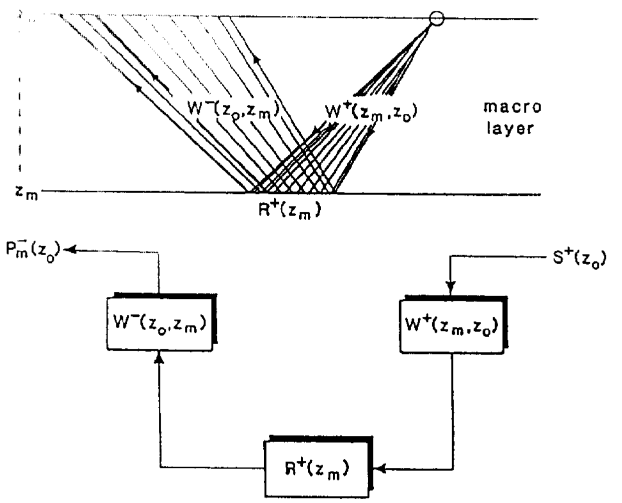


Figure 3. Propagation and reflection for one point source and one reflecting boundary, ignoring the reflectivity of the surface.

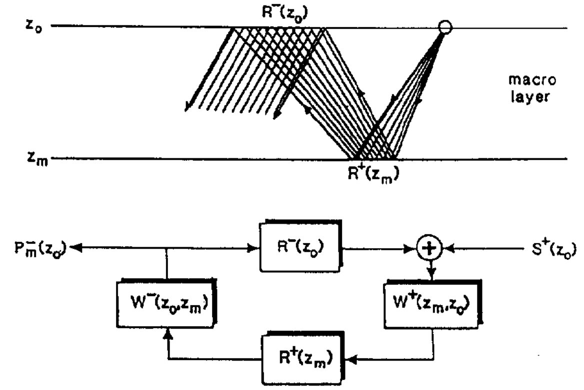


Figure 4. Propagation and reflection for one point source and one reflecting boundary, taking the reflectivity of the surface into account.

Description of seismic data. The primary information at the surface from an inhomogeneous subsurface can be elegantly presented mathematically. The expressions may be found in Chapter 6 of Berkhout's textbook *Seismic Migration: Imaging of Acoustic Energy By Wave Field Extrapolation: Volume A, Theoretical Aspects* (Elsevier, 1985). Since the mathematics is at an advanced level, this article treats the subject by illustration. The top of Figure 3 illustrates seismic propagation and reflection for one point-source at the surface (z_0) and one reflection boundary (z_m). Mathematically, the operators $\mathbf{W}^+$ (the downward propagation operator from z_0 to z_m), $\mathbf{R}^+$ (the reflection operator at the boundary for downward traveling waves), and $\mathbf{W}^-$ (the upward propagation operator from z_m to z_0) represent matrices, taking into account any type of vertical and lateral changes in the subsurface. The combination (see the bottom of Figure 3) of these operators and the source wave fields at the surface, represented by $\mathbf{S}^+(z_0)$, yield the well known data matrix containing all shot records $\mathbf{P}^-(z_0)$.

In practice, the surface is a strongly reflecting boundary and the mathematical expression has to be modified to include a reflection operator at the surface for upward traveling waves, $\mathbf{R}^-(z_0)$. Figure 4 is a graphic representation for one point source and one reflection boundary. In this case the expression for upgoing wave fields at the surface, represented by $\mathbf{P}^-(z_0)$, contains all surface-

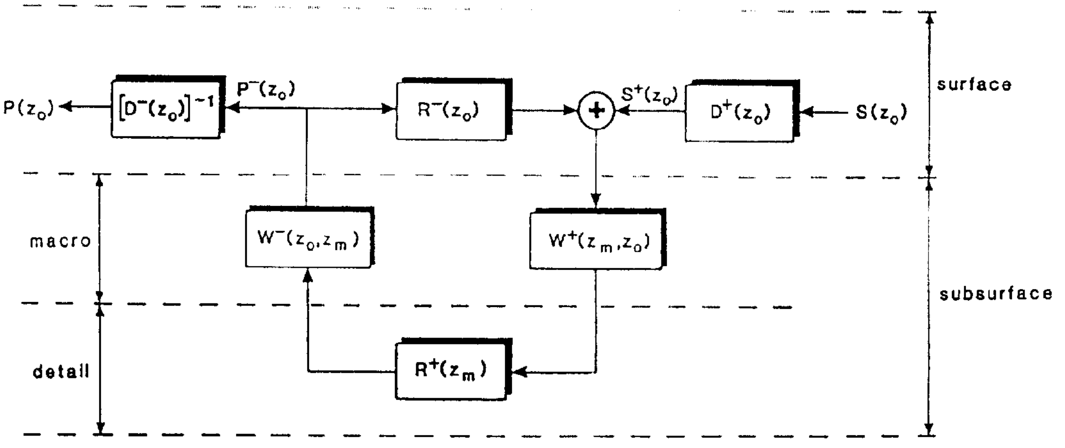


Figure 5. Summary on emission (at the surface), propagation, reflection (one reflecting boundary) and detection (at the surface).

related multiples. From simulations, it can be easily demonstrated that in practical situations, the multiple problem is largely caused by surface-related multiples.

The mathematics of propagation, reflection, and detection are graphically summarized in Figure 5. The decomposition operator $\mathbf{D}^+(z_0)$ transforms the source function into the downward traveling source wave field; at the other end, the decomposition operator $\mathbf{D}^-(z_0)$ transforms the measurements $\mathbf{P}(z_0)$ to the upward traveling reflected $\mathbf{P}^-(z_0)$. If the mathematics is formulated in a recursive way, source(s) and detectors can be positioned anywhere in the subsurface and the internal multiples in the propagation operators can be easily quantified. Finally, note that the direct wave has been deleted.

Inversion in steps. At first glance, it may appear attractive to aim at one large inversion scheme that transforms seismic measurements into rock and pore parameters. However, before we even think about the gigantic computation times involved, there are reasons to feel the development of one large inversion scheme may not be the best way to go. Figure 6 shows a stepwise inversion scheme, realized by three layers of software:

1. Surface-related preprocessing
2. Reflectivity imaging
3. Target-related postprocessing

The essence of the stepwise approach is that, before leaving one software layer, consistency checks should be made to approve the accuracy of the result. Those are the places where the interactive part of seismic processing preeminently fits. The processing in software layer 1 is based on discrete signal theory. Input as well as output are time sections. No specific information on the subsurface is required. Surface-related preprocessing should start with decomposition of measured data into downgoing and upgoing waves. The suppression of surface waves and the elimination of surface-related multiples is also included in software layer 1.

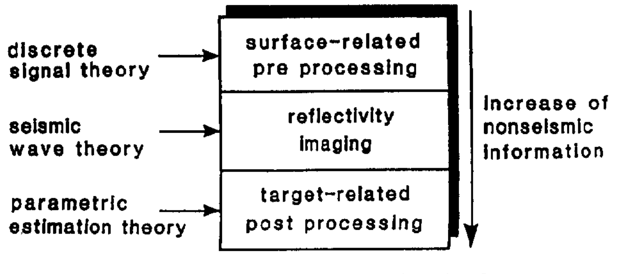


Figure 6. Stepwise seismic inversion, realized by three separate layers of software.

Note that conventional seismic processing (deconvolution, CMP stacking, time migration) should be considered as a surface-related method, providing a preview of the subsurface.

The output of the first software layer may be considered as deconvolved "primary" data that have been recorded at a nonreflecting, homogeneous data acquisition surface.

In software layer 2, the preprocessed data should first be used to determine the parameters of the macro subsurface model. The *P*-wave velocity (c_p) of each layer of an initial macro model is interactively adjusted so that the final estimate is fully consistent with stack velocity and/or traveltime values measured from seismic data. When information on a specific macro parameter is not available in the seismic data, heuristic relations are used (such as the Gardner relation to derive macro density for each layer).

The processing in software layer 2 is based on wave theory. The objective is to transform multioffset primary data to angle-dependent reflectivity for each subsurface point at each depth level of interest. This transformation requires inversion for the propagation operators. It can be shown (see Berkhout's text) that inversion for the downward propagation operator involves a spatial deconvolution process on the common detector gathers, and inversion for the upward propagation operator involves a spatial deconvolution process on the common source gathers. However, both spatial deconvolution processes can also be applied to one shot record at a time. It is now generally accepted that prestack migration per shot record is the way to go. In prestack migration it is common practice to reduce the migration output to one stacked reflection coefficient for each subsurface grid point (depth point), the stack being carried out over all available angles of incidence at each depth point (CDP stack). Hence, in CMP processing, common midpoint stacking is applied first, generally followed by zero-offset migration. In CDP processing, multioffset migration is applied first, generally followed by common depth point stacking. Moreover, in CDP processing, the coherency analysis on CMP gathers (to determine stacking velocities) is replaced by a coherency analysis on CDP gathers (to verify and update the macro model).

The angle-dependent subsurface reflectivity defines the input for the third software layer. To start (step 3a), angle-dependent reflectivity information of the target zone is selected and inverted to *P*- and *S*-velocity and density information (c_p, c_s, and ϱ) for each subsurface point, using the expression for the angle-dependent reflection coefficient, trend information (from the macro model) and, if available, crossplots between c_p, c_s, and ϱ in the target zone. Note that crossplots may play a very important role in information-based stabilization of inversion. For instance, a crossplot between ϱ and c_p has the important advantage that it will formulate a Gardner type relation that includes covariance information (stochastic reformulation), allowing the solution to be off

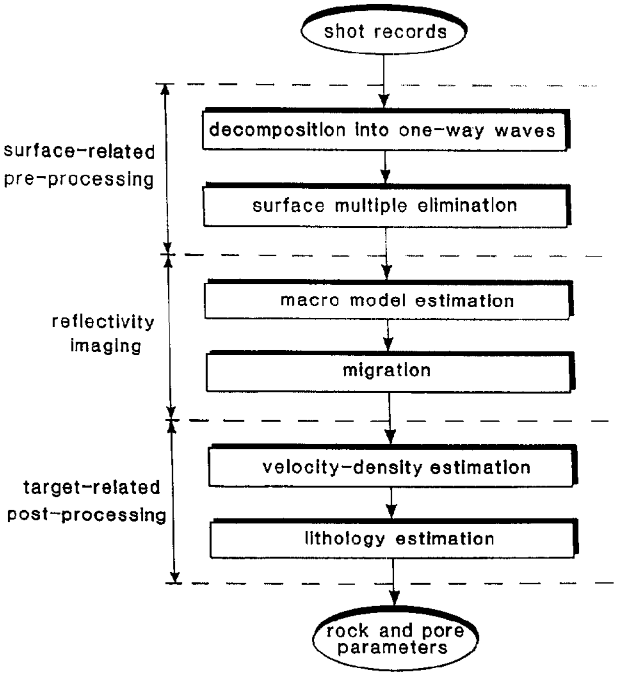


Figure 7. Acoustic version of the stepwise seismic inversion scheme.

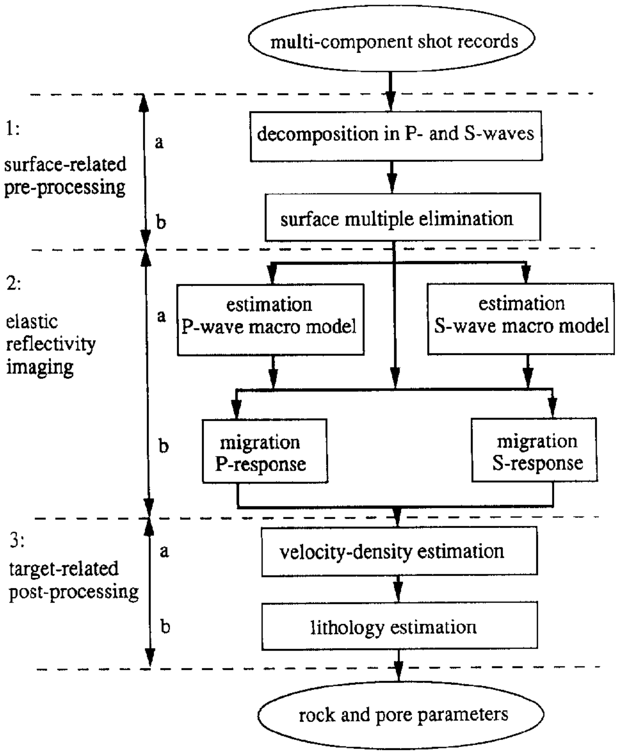


Figure 8. Elastic version of the stepwise seismic inversion scheme.

the mean curve. Note also that a linearized inversion results in weighted stacking of CDP gathers.

Finally, in the last inversion step (3b), the velocity and density information in the target zone is used to estimate:

- The rock parameters (density of the solid, compressibility of the solid, Poisson ratio of the bulk, frame strength factor)
- Pore volume parameters (porosity, water saturation)
- Pore fluid parameters (density of water, compressibility of water, density of gas and/or oil, compressibility of gas and/or oil)

The inversion algorithm makes use of Gassmann-type equations for the compressional and shear velocity, the volumetric average equations for the bulk density and the fluid compressibility, a linear change in depth for the Poisson ratio, a semiempirical depth function for the frame strength factor, and any other empirical relations available. First results show that lithologic inversion is only feasible if a significant amount of additional (nonseismic) information is used.

Figure 7 summarizes the stepwise approach to seismic processing (acoustic version). It may be considered as a functional outline for the new generation of seismic software. In the central second step, propagation effects and reflection information are separated (by migration). The validity of this critical and most time consuming part in seismic processing can be assessed by the evaluation of common depth point gathers. If, for a depth point in the target zone, the reflectivity information from different shot records is not aligned, then inversion step 3 should not be started; step 2 must be repeated with an updated macro model (via user interaction).

Stepwise approach to elastic inversion. The inversion process in step 3 is very difficult to carry out if only longitudinal reflectivity information is available. Use of the shear reflection coefficient is essential for accurate estimation of the shear velocity. (To a lesser extent, this also applies to the conversion reflection coefficients.)

Hence, step 3 makes it essential to follow the elastic approach. This means, on land, that ultimately three component sources and three component detectors must be used and that, in turn, will result in nine different data sets and each will contain a mixture of *P*- and *S*-wave data.

The stepwise elastic inversion process is graphically presented in Figure 8. In elastic preprocessing (step 1), it is important to start with the decomposition of the mixed data sets into data sets consisting of *P* or *S* data only (step 1a). This is done by transforming the three-component source excitations into downgoing potentials for *P*- and *S*-waves and by transforming the sensor particle velocity measurements into upgoing potentials for *P*- and *S*-waves. The theoretical background may be found in *Elastic Wave Field Extrapolation: Redatuming of Single- and Multicomponent Seismic Data* by Wapenaar and Berkhout (Elsevier, 1989). The *P*-wave potential in the elastic case plays the same role as pressure in the acoustic case.

The decomposed elastic data may contain significant multiple reflections and conversions related to the free surface. The next step then is similar to the acoustic case—elimination of surface related multiples and conversions. Again, the yield is nine different data sets.

In summary, the surface related preprocessing (steps 1a and 1b) transforms the vectorial data into a number of scalar responses in terms of "primary" upgoing *P* and *S* waves that are related to downgoing *P* and *S* source waves. As in the previously discussed acoustic case, any of the nine scalar data sets can be mathematically described in terms of downward propagation of the source wave into the subsurface, reflection at the different layer boundaries, and upward propagation of the reflected waves to the surface. If we include conversion at reflection and if we ignore converted waves during propagation, then we obtain nine independent scalar forward models which are each fully equivalent to the acoustic forward model.

It is now possible to perform elastic imaging (step 2) independently per scalar response. First, the macro models for *P*- and *S*-wave propagation are determined (step 2a). These macro models determine the properties of the propagation operators. Next, the propagation effects are removed from the data by prestack migration (step 2b) which results in structural images of reflectivity, optionally as a function of incidence angle. Finally, in target-related postprocessing (step 3), the angle-dependent reflectivity information is transformed via the detailed parameters (longitudinal and shear velocity, density) into the rock and pore parameters. LE