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Post-stack inversion of seismic reflection data from the belvoir coalfield

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Post-stack inversion of seismic reflection data
from the Belvoir Coalfield

by

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ABSTRACT

Post-stack inversion of reflection data in seismic exploration can be used to obtain detailed information about lithology variations in the zone of interest. Generalized Linear Inversion (GLI) has previously been applied as a useful tool to achieve this. The purpose of my investigation is to apply GLI to data from the Coal Measures. It is known that in the Coal Measures the most strongly reflecting horizons are the coal seams, which are the exploration targets. In the seismic bandwidth they are thin beds, which causes particular problems associated with vertical resolution for the inversion.

The method is applied to a seismic line from the Belvoir Coalfield supplied by British Coal. In order to get better relative amplitudes and to keep the same bandwidth down the whole section, the data were carefully reprocessed using the ProMAX software. Wireline log data from two boreholes intersected by the seismic line were edited to generate acoustic impedance logs as functions of time. Software was developed to implement GLI, and tested on synthetic data before applying it to the reprocessed data.

The initial guesses for earth and wavelet models at the boreholes were obtained after systematic studies to determine the best strategy. The construction of the initial guess for the boundary locations elsewhere on the section is very critical for the success of the search for the global minimum. A combination of structural interpretation and the inversion results obtained from the previous trace was found to do the best job. I have tried to invert separately for the boundary locations, acoustic impedances and the wavelet, with the wavelet parameterized in the frequency domain. I found that, provided that the wavelet extracted at a borehole is a good estimate with low error energy, the most successful strategy is just to invert for the boundary locations, keeping the acoustic impedances and the extracted wavelet fixed. If the extracted wavelet is not a good estimate, then parameterizing the wavelet in the frequency domain and optimizing those parameters at the borehole is a useful approach.

None of the implemented inversion strategies produced a perfect result. Discrepancies were due to the difficulty in obtaining true relative amplitude values on the processed section. The inversion results and systematic studies on the field dataset indicate that the assumptions of the convolutional model are not satisfied by the processed section.

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1 Introduction

1.1 Statement of the Problem

In the 1970s, seismic interpretation was still mainly limited to structural and stratigraphic interpretation of the subsurface. With the advent of better recording and processing techniques, preserving the amplitude information in the seismic data, attention has subsequently focused on linking subsurface rock and fluid parameters to the seismic amplitudes. 3-D seismic surveys, which have uniform areal coverage and obvious application to field appraisal and development, pushed this requirement further.

During recent years there has been an increasing demand for an integrated approach to reservoir characterization for the most effective recovery of in-place hydrocarbons (Archer et al., 1993). The characterization of reservoirs requires the integration of different data types to define a reservoir model. Geological, well log and core data are traditionally the most commonly used data sets in reservoir model-building (e.g. Raymer and Burgess, 1980). Well log data and core data provide detailed information about the vertical variation of many reservoir properties, but they are restricted to regions adjacent to the borehole. More recently, seismic data have played an increasingly important role in describing reservoirs away from the wellbore (e.g. Martinez et al., 1992). Because of their excellent lateral resolution, seismic data can contribute to a well-defined geometric description of structural and stratigraphic aspects of the reservoir (Graebner et al., 1981).

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Classically, seismic exploration consists of three main stages: data acquisition, data processing and geological interpretation. Inversion is the link between the last two stages and is one of the most active areas of current research in exploration seismology.

This thesis is concerned with the inversion of seismic reflection data from Coal Measures. The techniques developed are applied to synthetic data and also tested on real seismic and borehole data from the Belvoir Coalfield. British Coal has long experience of acquiring high resolution data of excellent quality to delineate faults for mine planning (Ziolkowski and Lerwill, 1979; Fairbairn et al., 1986). In the UK, there has also been much recent discussion about the potential for the development of coalbed methane (e.g. Cardy, 1995), which has led to a limited amount of drilling in coal basins traditionally exploited by mining (Creel, 1995). This gives rise to the requirement for high resolution seismic data, processed to identify the fine structures in the coal seams (i.e. washouts, faults and pinchouts) because coalbed methane is exploited by in-seam wells. Thus the ultimate goal of the work presented in this thesis is to develop inversion techniques for seismic data acquired from Coal Measures strata for application both in coal mining and in exploitation of coalbed methane.

1.2 Seismic Data Processing

Data processing is a sequence of operations which are carried out according to a pre-defined programme to extract useful information from a set of raw (normally observational) data (see Al-Sadi, 1980). The introduction of the digital computer in the early 1960s opened a new world in data processing. The great processing capabilities of computers have stimulated amazing technical advances in acquisition and interpretation as well as processing itself, leading to seismic reflection datasets whose quality and quantity could hardly have been imagined 30 years ago.

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According to Yilmaz (1987), there is a well-established sequence for standard seismic data processing. The three principal processes, deconvolution, stacking and migration, make up the foundation of routine processing. There are also some auxiliary processes that help improve the effectiveness of the principal processes.

Data processing is done to correct for statics, to suppress horizontally travelling noise, to correct the amplitude for spherical divergence and attenuation, to reduce distortions due to ghosts and reverberations, to broaden the bandwidth of the signal, to overcome the earth's attenuation, to suppress multiples and improve the signal-to-noise ratio by stacking, and to present stacked and migrated seismic sections that can be interpreted in terms of the underlying geology that produced the seismic response.

These procedures are general and basic in routine data processing. According to Yilmaz (1987), even when starting with the same raw data, the result of processing done by one organization seems to be different from that done by another organization. The differences often stem from differences in the choice of parameters and the detailed aspects of implementation of processing algorithms. This means that there is no single correct result for data processing, but the aim is to produce a seismic section which represents the subsurface geology as truly and clearly as possible for interpretation.

Based on the migrated section, inversion can be applied as an aid to interpretation.

1.3 Post-Stack Inversion

Post-stack inversion techniques have greatly developed since the beginning of the 1980s. At present they can be mainly divided into three categories. One category is wave equation inversion which includes the Born inversion method (Cohen and Bleistein, 1979; Bleistein et al., 1985); inversion by the generalized Radon transform (Beylkin, 1984;

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Miller et al., 1987); and the generalized pulse-spectrum technique (Chen, 1985). Another category is seismic tomography which includes ray travel time imaging (Aki, 1981); diffraction tomography (Dines and Lytle, 1979; Pan and Kak, 1983), and both in combination (Pratt and Goulty, 1991). The third category is generalized linear inversion (Bamberger et al., 1982; Cooke and Schneider, 1983; Oldenburg et al., 1983).

There are some other kinds of inversion techniques in the research stages, e.g. simulated annealing inversion (Sen and Stoffa, 1991) and genetic inversion (Stoffa and Sen, 1991). The classical recursive inversion technique (Lavergne and Willm, 1977; Lindseth, 1979) should be mentioned, but it is intrinsically unstable in the presence of noise.

For wave equation inversion, even though it uses all the information (travel times and waveforms) and has a strict mathematical derivation, there are still some shortcomings in its application: weak scattering assumption in the Born approximation and expensive computational time. For seismic tomography, the 2-D or 3-D images are computed very fast, but its disadvantages for surface seismic reflection data are that it generally uses only travel time information and the source-receiver geometry is far from optimum.

1.4 Generalized Linear Inversion

The category of generalized linear inversion methods is a very wide category. All the linear inversion methods can be drawn into it. The theory is described by Backus and Gilbert (1967, 1968), Sabatier (1977a, 1977b), Aki and Richards (1980) and Tarantola and Valette (1982). Previous work on it has been reported by Cooke and Schneider (1983), Oldenburg, et al. (1983), Cornish and King (1988) and Brac et al. (1992).

Oldenburg, et al. (1983) proposed that the inversion for acoustic impedance could be supplemented by two construction methods to find the missing high and low frequencies.

However, they said that the reflection response to a thin bed was a situation which would prevent them from obtaining a unique solution. Cooke and Schneider (1983) presented a least-squares inversion method with the introduction of the block earth model which corresponds to the method of Oldenburg et al. (1983). Furthermore, they introduced parameterization of the wavelet in the frequency domain which makes it possible to invert the effective wavelet simultaneously. But they had to put some constraints on the errors in initial guess model in order to ensure the solution was within the region of convergence. Even though both papers contained results from synthetic and field studies, they did not consider inversion if there was no well log information available. And most importantly they all did not try to solve the nonuniqueness of the inversion for acoustic impedance in sections containing thin beds.

Cornish and King (1988) presented a broadband constrained inversion by using a stochastic algorithm. Its application was shown by Martinez et al. (1992) for reservoir characterization. Brac et al. (1992) demonstrated their work for integrated statigraphic interpretation. All these authors concentrated on the acoustic impedance, because they assumed the boundary locations were correct from a priori information obtained by structural and statigraphic seismic interpretation. However, in thin bed cases such as coal seams, the boundary locations and acoustic impedance values are not independent (Widess, 1973).

I have been unable to find any published research about the GLI method being applied in thin bed exploration. Also there is no case history published using GLI based on the work of Cooke and Schneider (1983). In this thesis I investigate the application of the GLI method based on Cooke and Schneider (1983) to seismic sections in the Coal Measures. Previous published work (Cooke and Schneider, 1983) has failed to quantify inversion errors satisfactorily, apart from some simple error estimations made on synthetic examples (Weber, 1986), so a particular aim is to quantify the accuracy of the inversion results.

I adopt the forward convolutional model (Treitel and Robinson, 1966) used by both Cooke and Schneider (1983) and Oldenburg et al (1983). However, I do not think the reflectivity function produced by Cooke and Schneider (1983) is necessary or appropriate for post-stack datasets. In their article, they generated a reflectivity function in the Z-domain by recursive application of the following formula (Cooke, 1981):

$$R_j(x, Z) = \frac{C_j + R_{j+1}(x, Z)Z}{1 + C_j R_{j+1}(x, Z)Z} \quad (j=n-1,n-2,...,1,0) \tag{1.1}$$

Using the above algorithm, one can generate a one-dimensional synthetic seismic trace that includes all multiples and transmission losses for a given digitized impedance log and a source wavelet considered to be a plane wave. However, for some inverse problems, such as the post-stack inversion reported in this thesis, it will not be suitable because deconvolution, NMO corrections and stacking have been applied; a principle aim in applying these processing techniques is to suppress the multiples.

In my research, an improved GLI inversion method is presented and tested using a 2D seismic line passing through two logged boreholes. A post-stack dataset from British Coal, which was reprocessed using ProMAX to preserve amplitudes correctly (Yu, 1985; Mazzotti and Mirri, 1988), was used by applying the inversion to the stacked trace for the common depth point (CDP) gather located at one well. For this case, not only the acoustic impedance but also the lithology were known. Then the inversion result from the first trace was partly used as the starting model for next trace combined with some intepretative structure information. Upon reaching the CDP gather located at the other well, the inverted trace was compared with the known well logs. Their similarities and differences are analysed and the errors are quantified.

To avoid the conflict between the linear problem (amplitudes of reflection coefficients) and non-linear problem (locations of boundaries) presented by van Riel and Berkhout

(1985), in my improved GLI inversion an alternative two-step iterative inversion method (Redanz, 1988) is used.

Another problem in some previous work with the GLI method (e.g. Oldenburg et al., 1983) is that there has been no inversion of the extracted wavelet. To do this, I unwrap the phase spectrum of the wavelet (Shatilo, 1992) after extracting it as a Wiener shaping filter. Then the wavelet is defined in the frequency domain by eight parameters: four frequencies, a constant phase value plus linear and quadratic phase terms as functions of frequency, and an amplitude scaling factor.

To overcome the constraint on the accuracy of boundary locations in making the initial guess model (Cooke and Schneider, 1983), I adopt a two-part strategy. Firstly, an inversion for the reflection coefficient sequence in which the Jacobian matrix is calculated analytically (Dahl and Ursin, 1991) is used, if it is needed. Secondly, separate inversion steps are carried out for the boundary locations, acoustic impedance values, and the wavelet parameters.

For the thin beds encountered in coal exploration, which is the most difficult case for the inversion, I applied my inversion method to investigate which parameters are most sensitive to noise and which should be constrained for the inversion. Before the field data are inverted, some synthetic examples are studied.

2 Principles

2.1 Forward Model

A description of the least-squares inversion method begins with a definition of the forward problem. The forward model is used to calculate the seismic response of an earth model, in which x is the lateral coordinate and t is elapsed time. The seismic response depends on the seismic excitation characterised by an effective wavelet w(x,t) injected at the surface with onset at time zero. Here the mathematical model used for calculating the surface seismic response S(x,t) is the standard convolutional model:

$$S(x,t) = \int_0^\infty r(x,t-\tau)w(x,\tau)d\tau \qquad (2.1)$$

where r(x,t) is the primary reflectivity distribution of the medium, approximately related to the acoustic impedance distribution, A(x,t), by

$$r(x,t) \approx -\frac{1}{2} \, \partial/\partial t[\ln A(x,t)]. \qquad (2.2)$$

The convolutional model gives an alternative and complementary look at the seismic reflection method (Treitel and Robinson, 1966) compared to the wave propagation model, which describes the reflection method in terms of the laws of classical physics, i.e., Hooke's law and Newton's second law. It has produced an increased understanding of the relationship between geological features, such as pinchouts, facies changes, reefs and sand lenses, and the seismic response to such features. In addition to providing a basis for

interpretation of seismic data in terms of fine subsurface detail, the convolutional model has led directly to deconvolution and other time-sequence processing procedures.

The convolution model is a simplistic mathematical way to describe the physical phenomenon as well. Seismic theory in the early 1950s regarded a seismic trace as an entity that resulted from the solution of the wave equation with complicated initial and boundary conditions. As Robinson (1983) said: " Earthquake seismologists had obtained solutions in the case of very simple boundary conditions, but no comparable solutions had been obtained by exploration seismologists for any practical situation."

The convolutional model allows the impedance to be continuous, piecewise continuous, or discrete, and the earth's impedance is never discrete. With continuous impedance, the major reflections come from those impedance distributions in the earth that have periods that match the period of the effective seismic pulse. In effect, as the seismic pulse travels into the earth, it seeks out those impedance distributions to which it is tuned, i.e., those that have the same period as the effective pulse. One of the most significant results from the convolutional model is its demonstration that tuned events are most prominent, and this has laid to rest the fallacy that the largest reflections on seismic data are from discrete layering (White and Sengbush, 1987).

In this thesis, a discrete earth model is used to simplify the inversion problem. In discrete form the convolutional model of equation (2.1) may be written for a single trace as:

$$S = r * w \qquad\qquad (2.3)$$

where S is the digital seismogram of length m+n+1 samples, r is the reflection coefficient sequence of length n+1 samples, and w is the effective wavelet of length m+1 samples. Then the following summation is a general expression for the coefficients of S:

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$$S_i = \sum_{j=0}^{n} r_j w_{i-j} \ , \qquad i=0, 1, 2, \ldots\ldots, m+n. \qquad (2.4)$$

The discrete acoustic impedance distribution corresponding to the discrete reflectivity consists of a stack of n layers, in which the two-way travel times equal the time sample interval, bounded above and below by half spaces (Goupillaud, 1961). Thus the reflection coefficients for particle displacement may be expressed in terms of the acoustic impedance values as

$$r_j = \frac{A_j - A_{j+1}}{A_j + A_{j+1}} \ , \qquad j=0, 1, 2, \ldots\ldots, n. \qquad (2.5)$$

2.2 Inverse Problem

Actually, we are interested in the inverse problem. Given the recorded surface seismic section, we want to know the acoustic impedance distribution of the medium. A standard way of proceeding is to use least squares. Given a recorded digital seismogram S^{rec} of length N from the processed surface section, the aim is to minimise

$$\Phi = |F(A) - S^{rec}|^2$$
$$= \sum_{i=1}^{N} [F_i(A) - S_i^{rec}]^2 \qquad (2.6)$$

where $F(A)$ is the forward-modelled seismogram. The vector A represents the set of M 'model parameters'.

For example, the acoustic impedance values in equation (2.5) could be treated as the M unknown model parameters. Then, assuming that the wavelet is known (having been estimated previously), the forward-modelled seismogram can be calculated using equations (2.4) and (2.5) with an initial guess for the acoustic impedance values. In

practice, the forward-modelling schemes used in this thesis are variants on this scheme, for reasons given below, but the following algebraic development is general in that it allows for some non-linearity in the dependence of $\mathbf{F}$ upon $\mathbf{A}$. Having guessed an initial model $\mathbf{A}^0$, we linearize the relation between data and model by putting

$$\mathbf{F(A)} \approx \mathbf{F(A^0)} + \mathbf{Ga}, \tag{2.7}$$

where

$$G_{ij} = (\frac{\partial F_i}{\partial A_j})_{A=A^0}, \tag{2.8}$$

and

$$\mathbf{a} = \mathbf{A} - \mathbf{A}^0. \tag{2.9}$$

Putting $\mathbf{d} = \mathbf{S}^{rec} - \mathbf{F(A^0)}$, we get

$$\Phi \approx |\mathbf{d} - \mathbf{Ga}|^2.$$

Minimizing Φ, the least-squares solution is found (Aki and Richards, 1980)

$$\mathbf{a}^L = (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\mathbf{d}, \tag{2.10}$$

where $\mathbf{G}^T$ is the transpose of matrix $\mathbf{G}$.

The standard linearization-iteration proceeds by constructing the second model $\mathbf{A}^1 = \mathbf{A}^0 + \mathbf{a}^L$, revising the linear relation by putting

$$F(A) \approx F(A^1) + Ga,$$
(2.11)

where now

$$G_{ij} = (\frac{\partial F_i}{\partial A_j})_{A=A^1},$$
(2.12)

and repeating the minimization process.

In practice, the above process may not converge (Hartley, 1961). A remedy is to construct the second model as

$$A^1 = A^0 + Ka^L,$$
(2.13)

where $0 < K \leq 1$. Even with small K, failure to converge is not uncommon.

An entirely different approach is the gradient method, in which the direction of most rapid change of Φ is obtained in the model space. Since the equation of a plane tangent to the surface $\Phi = $ constant at $A = A^0$ is given by

$$\sum_j \frac{\partial \Phi}{\partial A_j}(A_j - A_j^0) = 0,$$
(2.14)

the direction of most rapid change is normal to the plane, and is given by the vector a^G, with components $(- \partial\Phi/\partial A_1, - \partial\Phi/\partial A_2, \ldots, - \partial\Phi/\partial A_M)$, evaluated at $A = A^0$.

From (2.6),

$$\frac{\partial \Phi}{\partial A_j} = 2\sum_i (S_i^{rec} - F_i(A)) \frac{\partial F_i}{\partial A_j}$$

$$= 2 \sum_i d_i \frac{\partial F_i}{\partial A_j}$$

$$= 2 \sum_i G_{ij} d_i \, , \qquad\qquad (2.15)$$

and $\mathbf{a}^G$ is parallel to $\mathbf{G}^T\mathbf{d}$.

Adjustment of a model by the gradient method can always be made to converge towards a minimum for Φ. The convergence, however, may be very slow. On the other hand, the least-squares iteration converges very rapidly when it does converge. The vectors $\mathbf{a}^G$ and $\mathbf{a}^L$ are often nearly 90 degrees apart from each other.

It therefore seems reasonable to take an intermediate direction between $\mathbf{a}^G$ and $\mathbf{a}^L$. Marquardt (1963) shows that the damped least-squares solution,

$$\mathbf{a}^M = (\mathbf{G}^T\mathbf{G} + \varepsilon^2\mathbf{I})^{-1}\mathbf{G}^T\mathbf{d} \qquad\qquad (2.16)$$

points in such an intermediate direction. In fact, when $\varepsilon^2=0$, $\mathbf{a}^M = \mathbf{a}^L$; and when $\varepsilon^2 \to \infty$, the direction of $\mathbf{a}^M$ approaches that of $\mathbf{G}^T\mathbf{d}$, and therefore of $\mathbf{a}^G$. For a small ε^2, the process may diverge, and for a large ε^2, the convergence may be too slow. After a few trials, an optimal ε^2 may be found for rapid convergence.

In (2.16), $\mathbf{G} = \partial F_i/\partial A_j$ is called the sensitivity matrix or Jacobian matrix, ε^2 the damping factor, and $\mathbf{I}$ is the identity matrix. The damping factor ε^2 can be calculated analytically as discussed by Marquardt (1963), or it can be chosen in an empirical manner as was done by Cooke and Schneider (1983). The empirical method searches for the ε^2 that minimises the root-mean-square (rms) error between the data being inverted and the synthetic seismogram generated from the corrected initial guess. The corrected guess, and thus the associated synthetic, is a function of ε^2 according to equations (2.9) and (2.16). This method is also known as the Generalised Linear Inversion method (GLI).

2.3 Inversion for the Reflection Coefficient Sequence

The simplest least squares scheme for inverting the observed seismograms is to use equation (2.4) to invert directly for the reflection coefficients. This requires that an estimate of the effective wavelet is available, so the wavelet coefficients are fixed. In this case the relationship between the reflection coefficients and the observed seismic trace is linear. With the notation of equation (2.4), equation (2.12) can be rewritten as

$$G_{ij} = (\frac{\partial S_i}{\partial r_j}) = w_{i-j} .$$

(2.17)

Then the reflection coefficient sequence r can be found by using equations (2.16) and (2.9). Because the problem is linear, the inversion is carried out once only (without iteration), unless it is desired to try different values of the damping parameter ε^2.

This simple scheme does not itself invert for the acoustic impedance function. However, in some circumstances, it is useful for obtaining an initial guess acoustic impedance model before inverting for a parameterized wavelet and parameterized earth model, as described in the following section. It is equivalent to designing a Wiener shaping filter, corresponding to the reflection coefficient sequence, which does the best job in a least-error-energy sense of shaping the wavelet into the observed trace.

2.4 Model Parameterization

The earth's impedance is a continuous function in depth or time (as it is measured here). It is advantageous to approximate this function as a restricted number of layers in order to

Figure 2.2 The amplitude spectrum of the cosine-tapered-box-car wavelet.

Amplitude

A0=1.0
f1=20 Hz
f2=30 Hz
f3=90 Hz
f4=200 Hz

Stratigraphic Column

Impedance

Time

Real Earth

Discrete Interval Parameterization of Earth
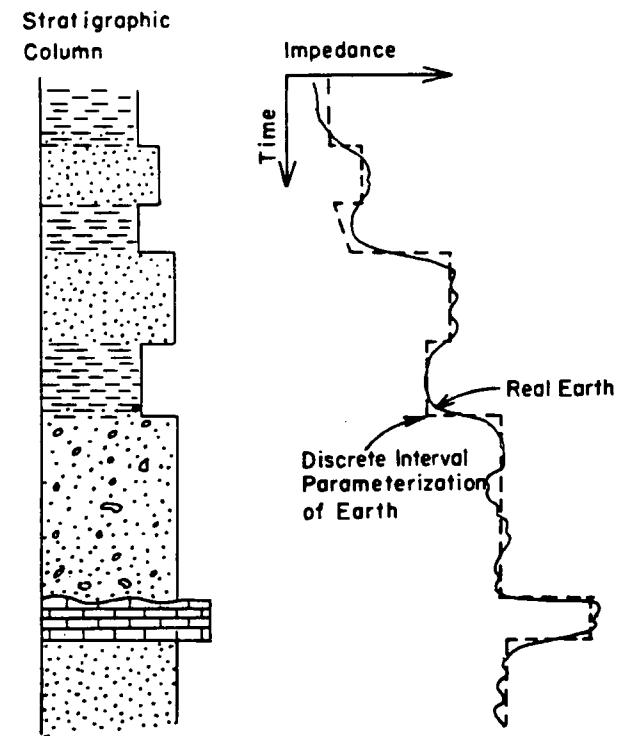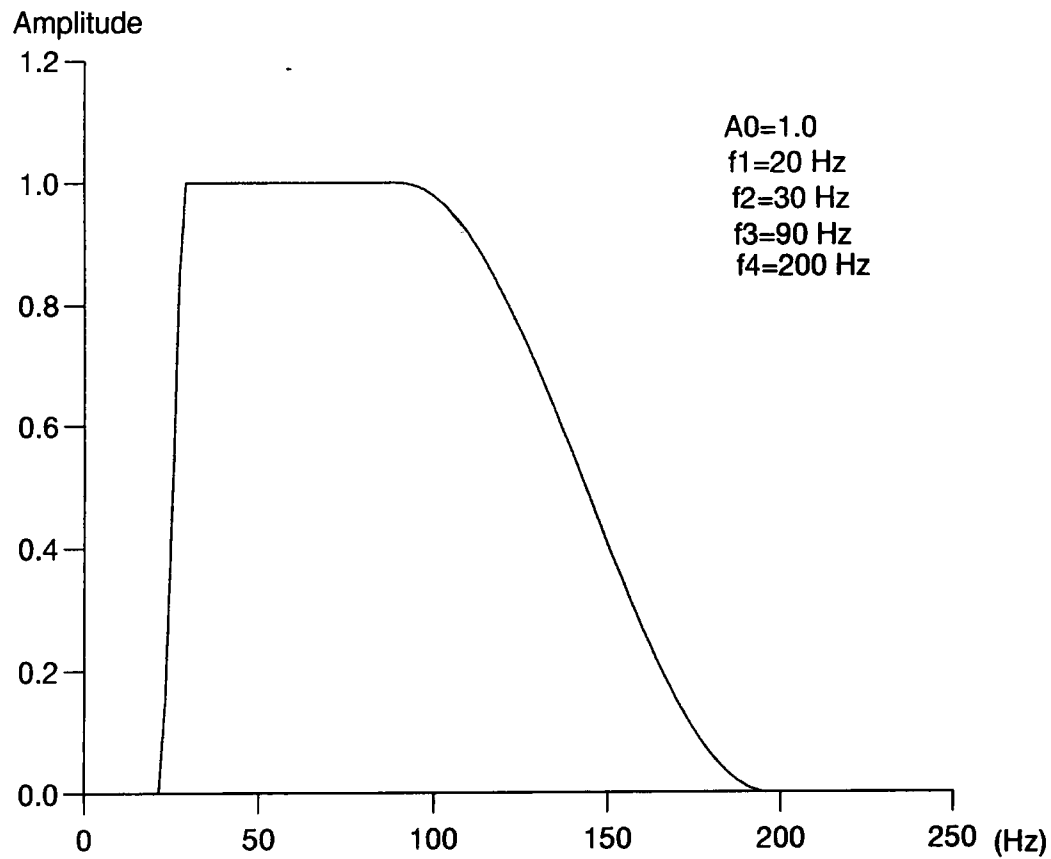
Figure 2.1 Continuous discrete interval parameterization.

avoid problems such as (1) singular matrices or instability in inversion; (2) excessive costs in computer time and storage; (3) underconstrained inversion when extra model parameters are added; and (4) vertical resolution problems caused by non-linearity in boundary locations, which will be discussed in next section. The parameterization used in this thesis includes both the earth model and the wavelet. The principle for the parameterization is to use as few parameters as possible to represent the main features in the seismic response.

The parameterization describes the earth in terms of separate blocks or lithologies and is termed "discrete interval parameterization". Each lithic unit has assigned to it (a) a variable two-way time at the bottom of the block; (b) a variable impedance value at the top of the block; and (c) a variable linear rate of change of the impedance within the block (the impedance gradient). Figure 2.1 demonstrates this discrete interval parameterization method with the continuous earth model. Theoretically, the introduction of the impedance gradient makes it possible to restore the low-frequency trend of the impedance, whereas other methods can only get it by other means (from velocity analysis or by interpolation between wells) and not from the inversion itself. That is to say, the possible advantage of this inversion method is that it could widen the bandwidth.

In the above section on the forward model, it is assumed that one knows the effective wavelet that is to be convolved with the reflectivity function. This is not the case with real seismic data, so the effective wavelet must be treated as an unknown and solved for in the same manner as the impedance. The unknown wavelet is parameterized in the frequency domain where it is described by the four frequencies that constitute a band-pass filter (Fig. 2.2), up to three phase parameters and an amplitude. The form of the wavelet phase spectrum adopted here is

$$\Phi(f) = \varphi_0 + \varphi_1 f + \varphi_2 f^2. \tag{2.18}$$
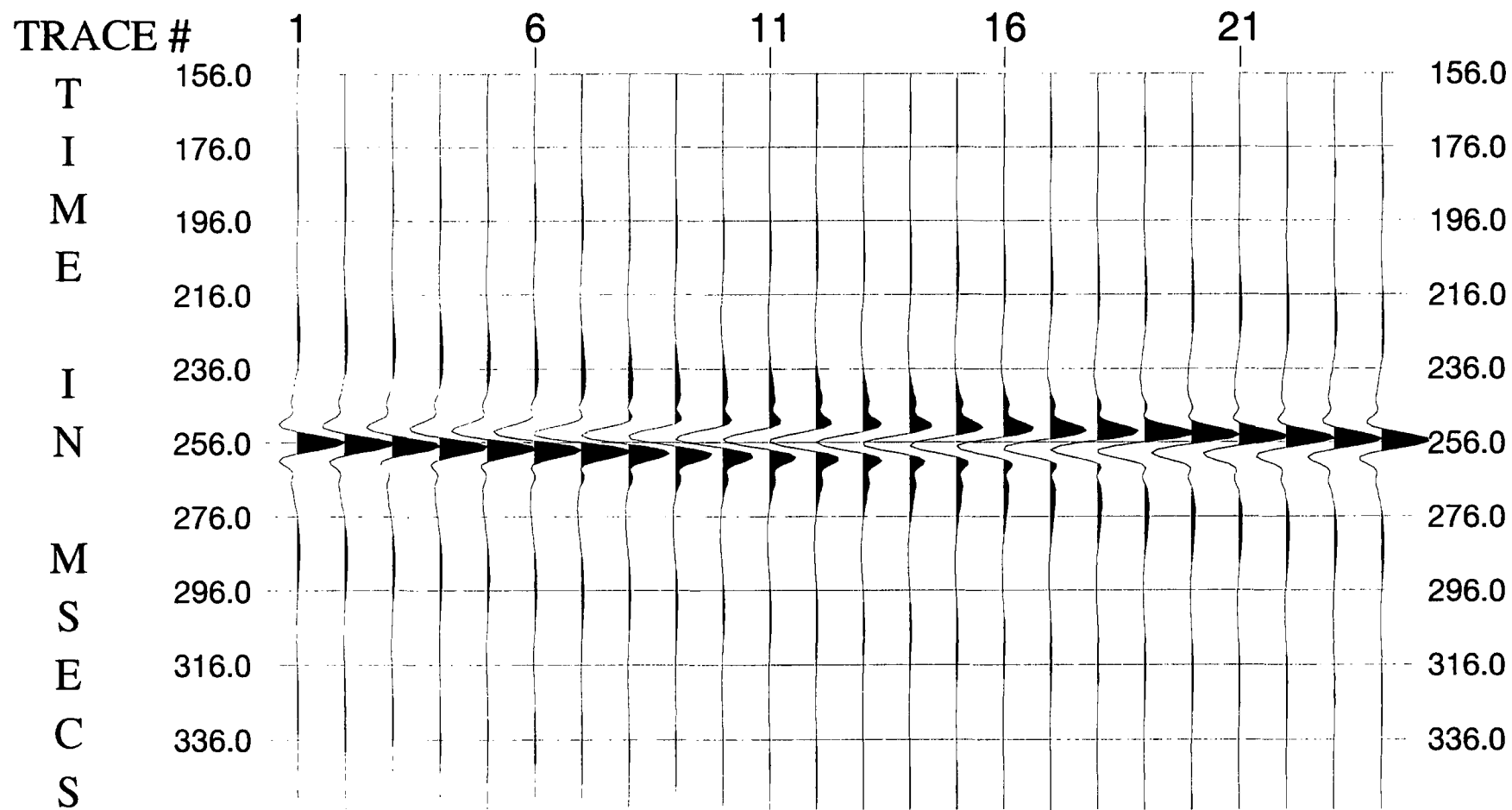
Figure 2.3 The effect on a zero-phase wavelet of changing the constant phase φ_0 in steps of - 15 degrees.
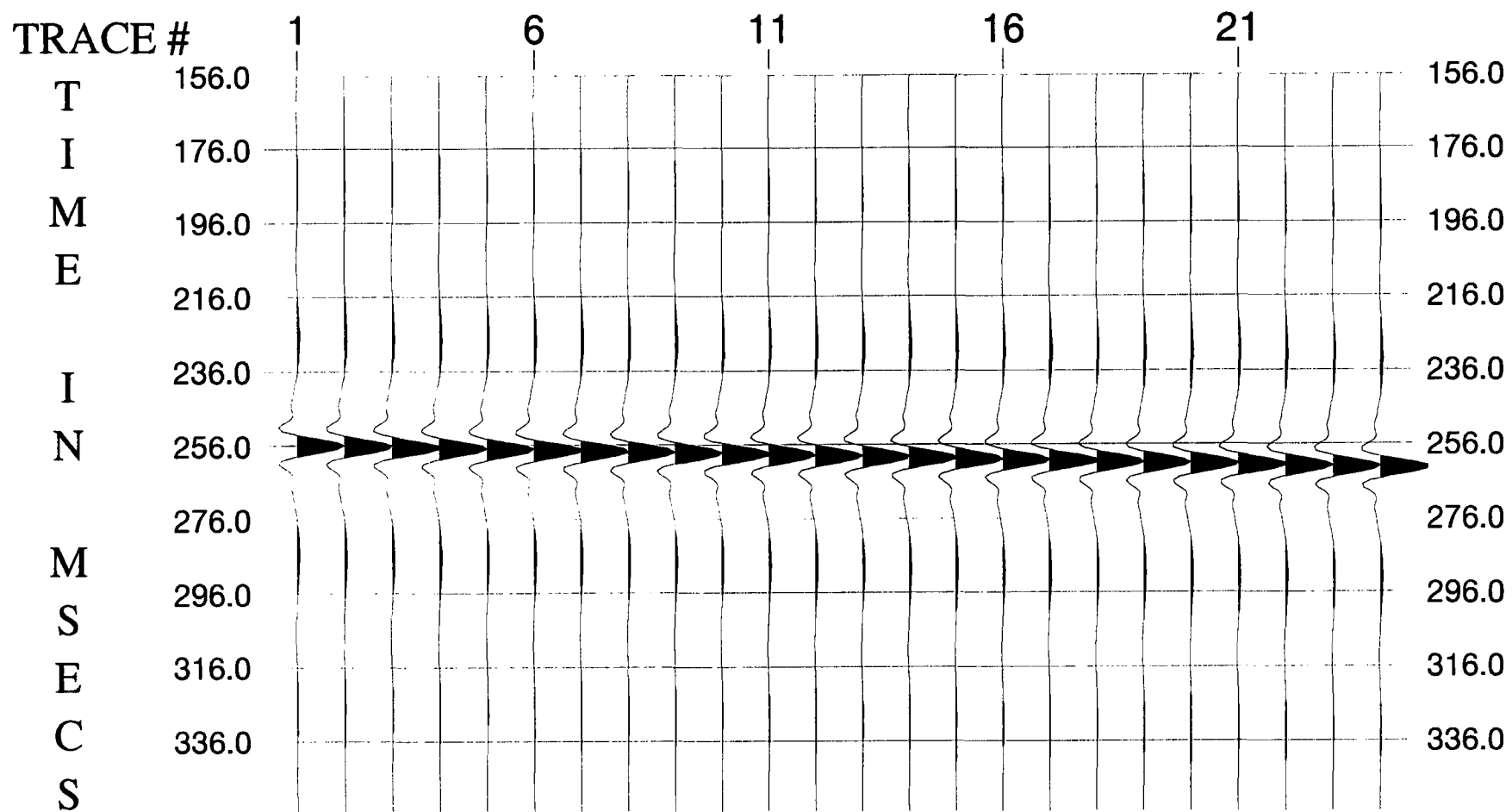
Figure 2.4 The effect on a zero-phase wavelet of changing φ_1 in steps of - 0.1 deg/Hz.
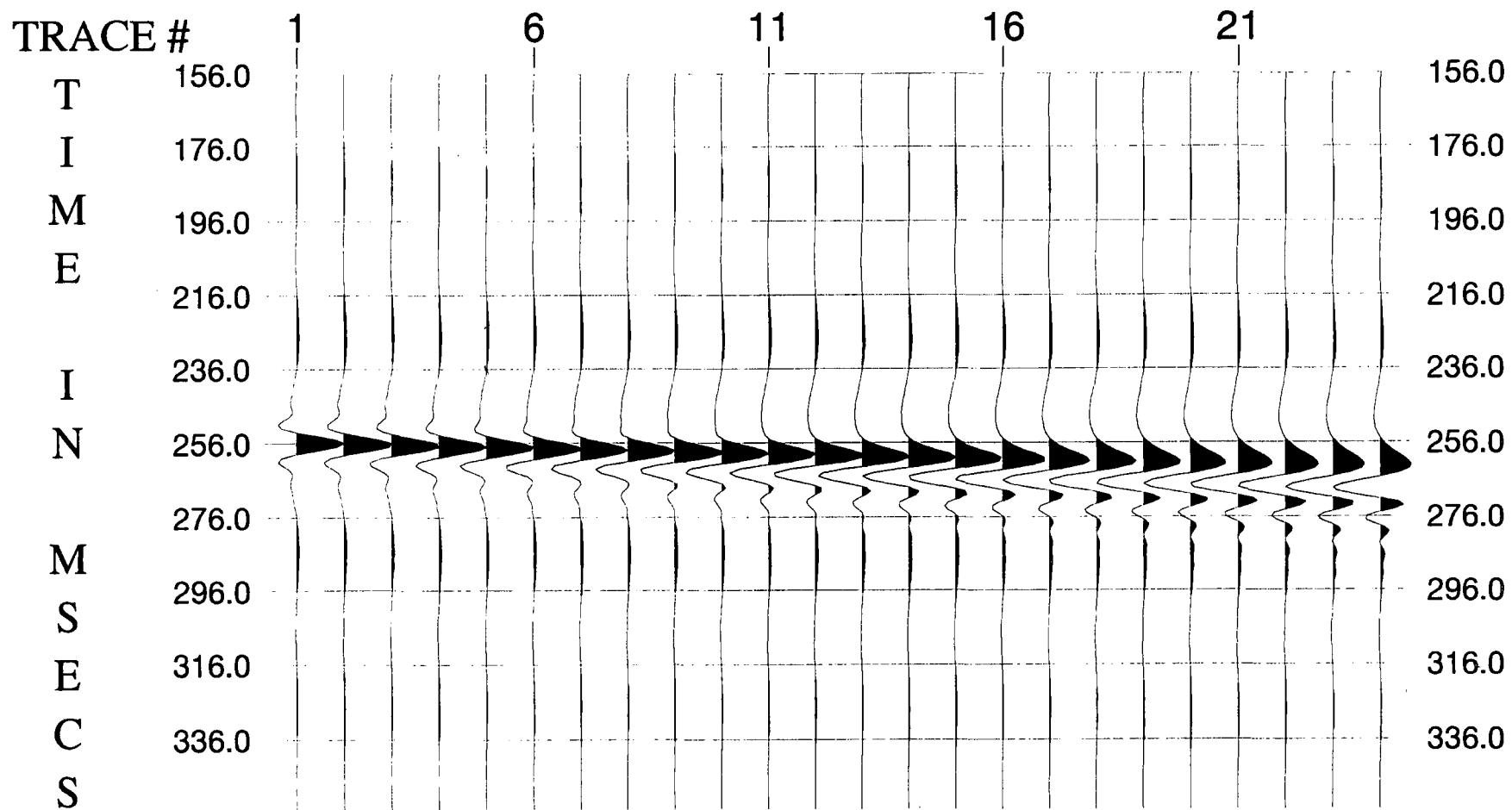
Figure 2.5 The effect on a zero-phase wavelet of changing φ_2 in steps of - 0.001 deg/Hz^2 .

The family of wavelets used here have amplitude spectra which are cosine-tapered box-cars defined by four frequencies (Bracewell, 1978). The cosine tapers have the effect of suppressing the side-lobes at the cut-off frequencies in the time domain. This type of wavelet is commonly used in seismic modelling.

The following three figures demonstrate the effect of varying each phase parameter independently. Figure 2.3 shows how the shape of the wavelet changes as the constant phase value at all frequencies, φ_0, is incremented in steps of -15 degrees starting with zero phase. Figure 2.4 shows the effect of changing the value of φ_1 in increments of -0.1 degree/Hz, which simply shifts the wavelet in the time domain. Figure 2.5 shows the effect of changing the value of φ_2 in increments of -0.001 degree/Hz^2. The amplitude of the wavelet enables us to scale the forward-modelled trace with the observed trace.

Because these parameters are implicit in equation (2.12), it is impossible to calculate the Jacobian matrix analytically. This problem will be discussed in Chapter 3. GLI using this type of model is called GLI with parameterization.

2.5 Vertical Resolution

The convolutional model of equation (2.1) may be rewritten for a discrete reflectivity model as

$$S(t)=w(t)*r(t)$$
$$=\sum_{j=1}^{n} r_j w(t - \tau_j)$$

(2.19)

where r(t) is the reflectivity model consisting of N reflectors:

$$r(t) = \sum_{j=1}^{n} r_j \delta(t - \tau_j)$$ (2.20)

with reflection coefficients r_j and corresponding boundary locations (i.e. two-way times) τ_j. We can see that S(t) depends linearly on the values of r_j, but nonlinearly on the values of τ_j.

According to the analysis by Van Riel and Berkhout (1985), the solution obtained by generalized linear parametric inversion is usually superior to the resolution obtained by inversion with a convolutional inverse filter, or at least equal to it in the worst case. In parametric inversion the reflectivity function is represented as a parameterized earth model with a limited number of reflectors (blocks) as fewer unknowns, whereas in wavelet inverse filtering the reflectivity function is a regularly sampled function where every sample point represents an unknown, so there are many more unknowns. Of course, to formulate an initial guess for a parametric model, a priori information is required. This information may be available from various sources, e.g., log data, data on regional geology, or results from petrophysical analysis. The reason for the improved resolving power of the parametric approach is that a priori information is explicitly used. The effort of collecting sufficient a priori information is the cost of increasing resolution beyond that offered by wavelet inverse filtering.

GLI with model parameterization and least squares inversion for the reflection coefficient sequence correspond to these two different inversion methods. I found each method useful in different circumstances, and in different positions in the inversion sequence. Because inversion for the reflection coefficient sequence has lower vertical resolution, but no prior earth information is required, it is used to search for a guess model for boundary locations when the guess model obtained by inverting the previous trace is not suitable. It is necessary that an estimate of the effective wavelet is available. Circumstances where it could be used are where there is a fault or a stratigraphic change (e.g. pinchout), or even

in some area with a low signal-to-noise ratio (SNR). After inverting for the reflection coefficient sequence, the approximate boundary locations for each block can be obtain by analysing the reflectivity function. The previous acoustic impedance values for each layer are used to form the new guess model, on the assumption that there are no gross sudden lateral changes in lithology. Then this guess model is used to continue the inversion by GLI with model parameterization.

Recent research by Okaya (1995) shows that the spectral amplitude response of thin beds has bands and notches whose periodicites are directly related to layer thickness. An "optimally" tuned reflection occurs when the fundamental spectral amplitude band in the reflectivity response is excited by a seismic source. Distinct (resolved) reflections from the two interfaces occur when at least the fundamental and second amplitude bands are preserved. These considerations are directly relevant to my work as coal seams are the predominant reflecting horizons, as well as being the target horizons, and they are most certainly thin beds in terms of their reflection response to the seismic source.

Gochioco (1992) concluded that, "High-resolution seismic surveys applied to coal exploration indicated the existence of complex problems associated with interference reflections in the recorded wavefield data". He showed how two dominant coal seams and a rider seam could easily affect the resulting reflection by their thickness, separation distance, and sequence layering.

2.6 Error Energy and Correlation Coefficient

In order to measure the quality of the least-squares inversion between the forward-modelled trace S(t) and the observed trace X(t), an error energy function was defined by

$$E = \left\{ \frac{\sum_i [S(i) - X(i)]^2}{\sum_i [X(i)]^2} \right\} \times 100\% \tag{2.21}$$

If E equal to 0 that means two traces are exactly the same, which shows that this error energy also can measure the quality of the match between them. Apart from this, a correlation coefficient is defined to describe the similarity of these two traces, especially when they are not normalised:

$$C = \frac{[\sum_i S(i)X(i)]^2}{\sum_i S^2(i) \sum_i X^2(i)} . \tag{2.22}$$

It is easy to see that $0 \leq C \leq 1$. When C equals to 1 that means two traces looks exactly the same, but may have a constant factor difference. These two concepts are useful for later discussions.
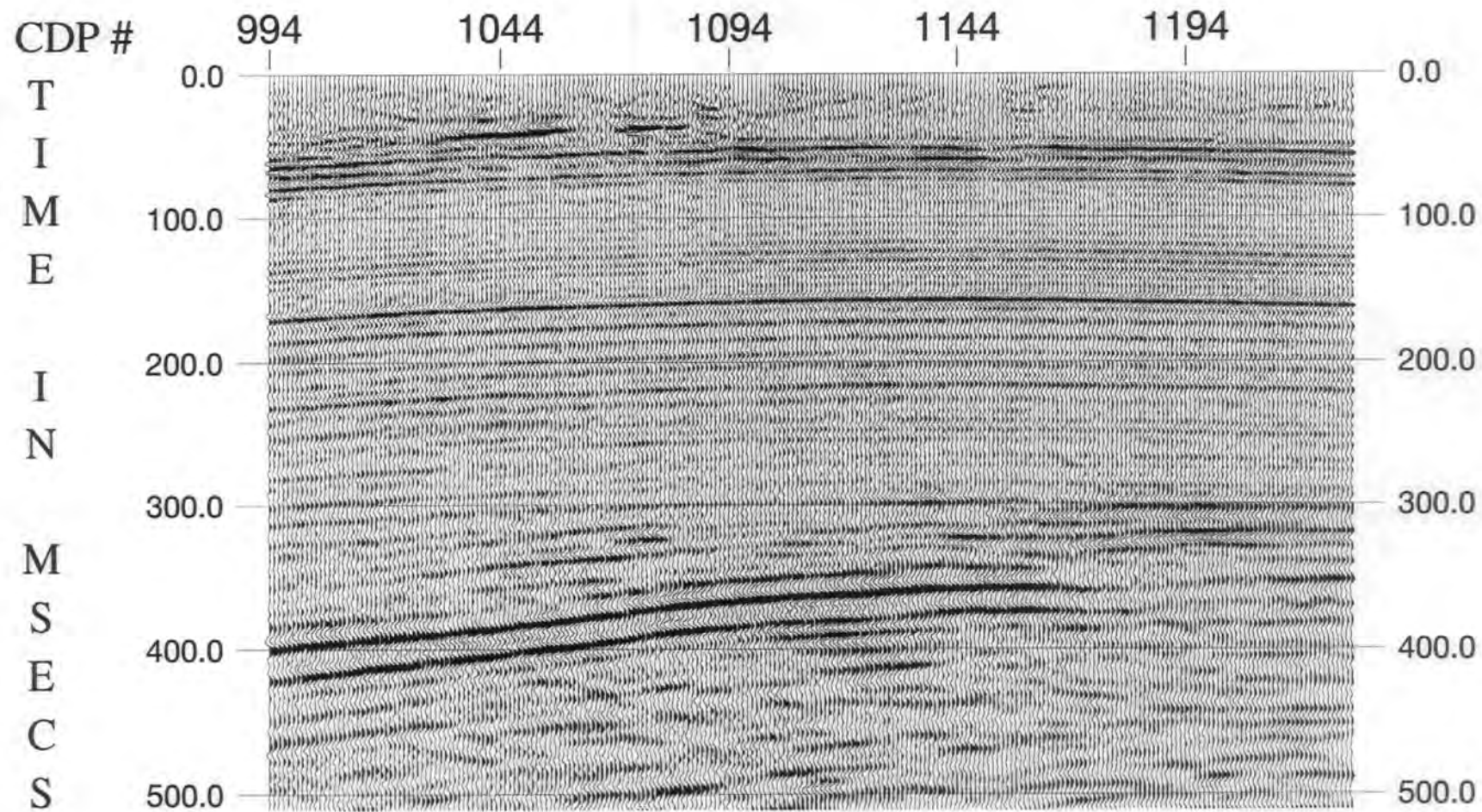
Figure 3.1 The migrated seismic section processed by British Coal.

LINE 87-AFY-04 MIGRATED STACK
PROCESSING SEQUENCE

PROCESSED DURING JULY-DECEMBER 1987
PROCESSING SAMPLE RATE   1 MS
PROCESSING LENGTH   1.5 SECS

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

1 DEMULTIPLEX AND POLARITY REVERSAL
2 SPHERICAL DIVERGENCE AND GAIN CORRECTION
3 TRACE EDIT
4 CDP GATHER
5 FIRST BREAK SUPPRESSION MUTE
6 SYSTEM RESPONSE FILTER
7 PREFILTER   (25-OUT HZ HIGH PASS FILTER)
8 TIME INVARINT DECONVOLUTION   (TYPE-WHITENING)
        OPERATOR LENGTH 51 MSECS
        DESIGN GATE :-
        ZERO METERS OFFSET: 70 MS -- 1000 MS
        580 METERS OFFSET   : 400 MS -- 1000 MS
9 FIELD STATIC CORRECTIONS CALCULATED USING UPHOLE
        STATIC METHOD   (DATUM: CURVED SEE HEADSTRIP)
10 VELOCITY ANALYSIS
11 AUTOMATIC RESIDUAL STATIC CORRECTIONS
     SURFACE CONSISTENT STATICS (MAXIMUM STATIC: +/- 4MS)
     3 TRACE PILOT   CORRELATION GATES: 25 - 450 MS
12 VELOCITY ANALYSIS WITH 30 CDP CONSTANT VELOCITY STACK
13 AUTOMATIC RESIDUAL STATIC CORRECTIONS
     SURFACE CONSISTENT STATICS (MAXIMUM STATIC: +/- 4MS)
     3 TRACE PILOT   CORRELATION GATES: 45 - 500 MS
14 NORMAL MOVEOUT CORRECTIONS
15 NORMAL MOVEOUT STRETCH MUTING
16 TIME INVARIANT EQUALIZATION
17 CDP STACK
18 TIME VARIANT DIGITAL BANDPASS FILTER
        FILTER LENGTH : 401 MS
        SP RANGE : 109-867
        0 - 200 MS   60 - 200 HZ
        300 MS   40 - 160 HZ
        500 - 600 MS   30 - 140 HZ
        1000 - 1500 MS   25 - 100 HZ
        LOCUT SLOPE 4DB/HZ   HICUT SLOPE 2DB/HZ
19 TIME VARIANT EQUALIZATION (6 BALANCE GATES)
20 F-K FILTER
21 FD MIGRATION (65 DEGREE DIP)

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Figure 3.2 The processing sequence table used by British Coal.

3 Methodology

3.1 Data Processing

3.1.1 Introduction

The seismic dataset I used is line ASFORDBY 87-AFY-04 from the Belvoir coalfield, acquired by the British Coal Corporation who kindly supplied me with the raw data and a fully processed section (Fig. 3.1). Its processing sequence is tabulated in Fig. 3.2.

The quality of British Coal's processing is high, but their objective was to maximize SNR and resolution for interpretation, and not to pre-condition the stacked data for inversion. For example, they used a time-variant digital bandpass filter after stack to improve SNR, which will definitely have changed the amplitude spectrum along the trace, but the wavelet should be constant for inversion based on the convolutional model. Consequently I decided to reprocess the dataset from the field records using ProMAX in the Department of Geological Sciences, University of Durham.

The dataset has a total of 190 shots and each shot has 116 traces with a group spacing of 5 m. The record length is 3 seconds and the sample interval is 1 ms. CDP gathers are numbered from 206 to 1804 with a spacing of 2.5 m.

There are two boreholes on the line named Thorny Plantation and Pillbox, located at CDPs 994 and 1230, so I concentrated on the section over this range in order to compare the inversion results with the well logs. That is to say, only about 500 CDPs (851-1350)
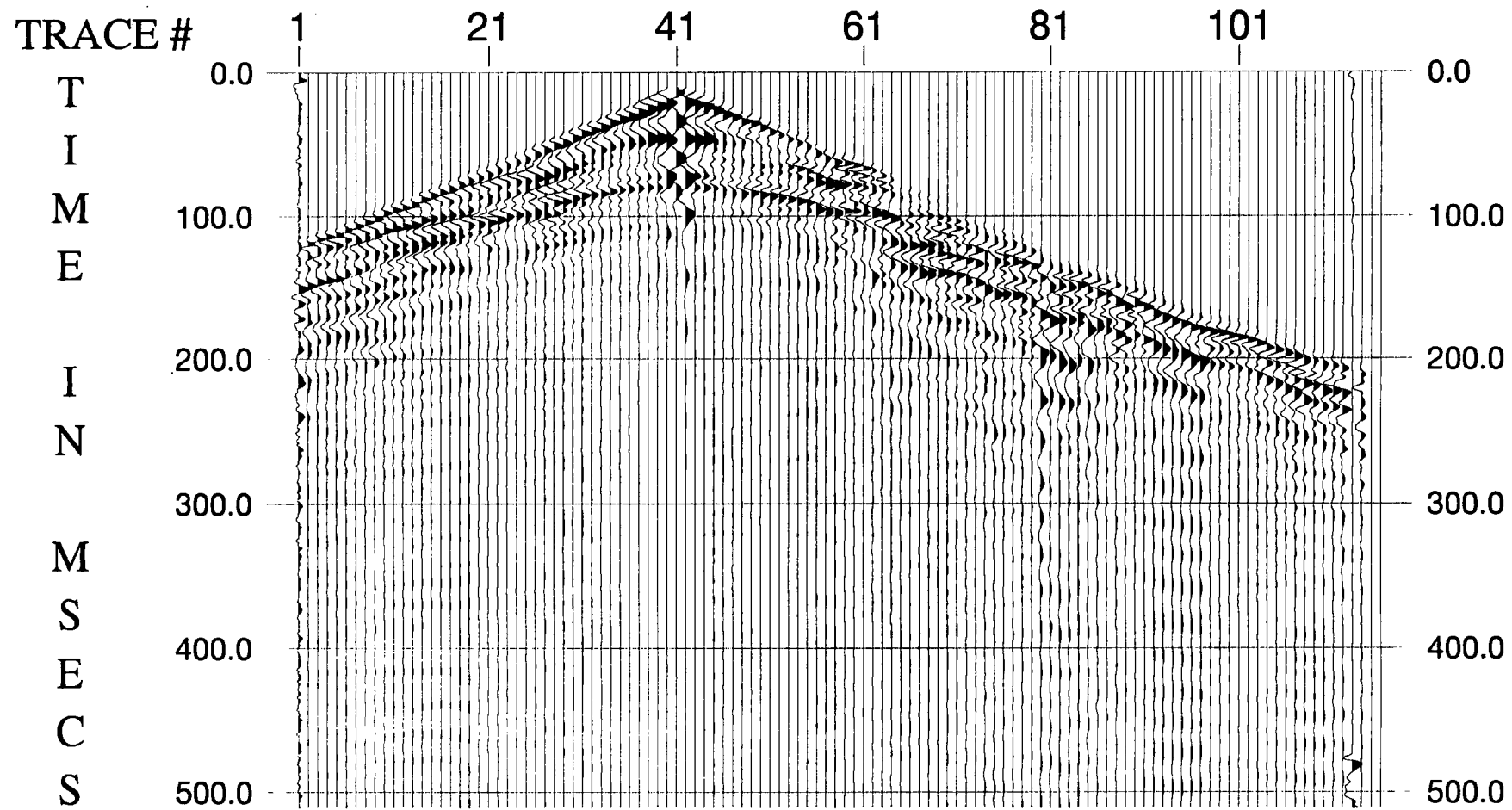
Figure 3.3 The original recorded data from shot No. 85.

comprise the study area for testing the inversion methodology. Since the main coal seams are all above 500 ms, the processing length I chose was 512 ms.

3.1.2 Trace Editing and Geometry Editing

First all the recorded data in SEG-Y format were input from a 8 mm data cartridge. The "Screen Display" was used to edit out noisy traces (traces 1 and 113) and reverse traces (trace 41) with the wrong polarity as shown in Fig. 3.3 for shot number 85. "Trace Kill" and "Trace Reverse" were used to edit these traces.

"Geometry Editing" involves several files to edit. The files should contain information about the elevations of sources and receivers, hole depths, uphole times and the statics at source and receiver locations. The generating file is geom_file which can also be edited without interpolation.

The next step is "Geometry Installation" to set up the database and initialize it with all of the necessary geometry information. There are four steps: (1) "Header Fixup" (correct channel number and end-of-ensemble problems in trace headers); (2) "Initialize" (initialize a dataset and the database); (3) "Load Geometry" (load the geometry specified in 'geom_file' to the database); (4) "Load Headers" (load geometry info from the database to the dataset trace headers). The "Header Fixup" step is optional, and should only be used when problems exist. The other steps are required, and should be run one at a time or run all together by choosing "Combination".

3.1.3 True Amplitude Recovery and Trace Muting

True amplitude recovery applies a single time-variant gain function to traces to compensate for loss of amplitude due to spherical divergence (wavefront spreading), transmission losses and anelastic attenuation.
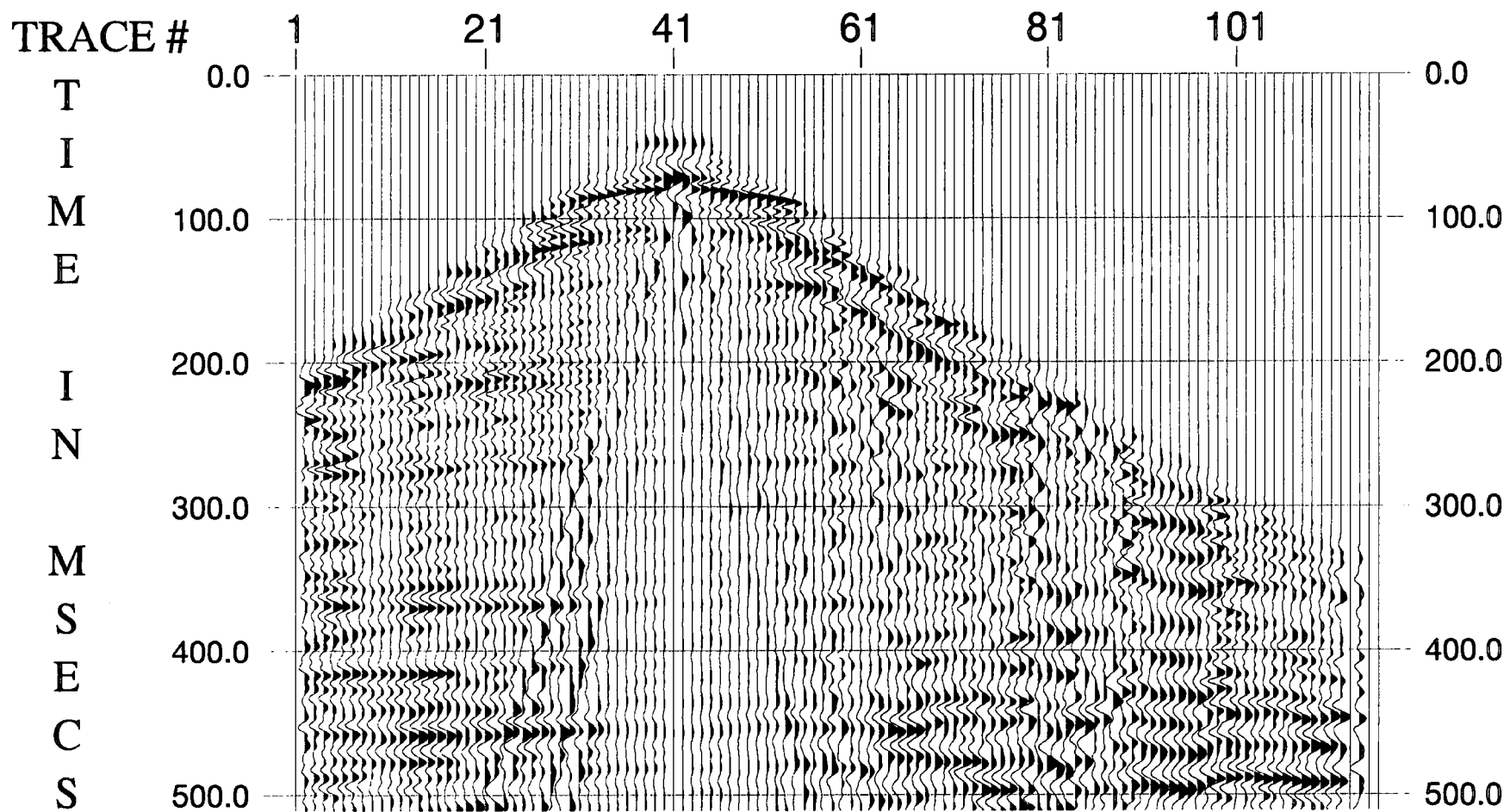
Figure 3.4 The same dataset as Fig. 3.3 but with editing and muting.

Spherical divergence corrections may be based on the reciprocal of the distance that the wavefront has travelled, using the "1/dist" option. Alternatively, corrections may be based on a function of travel time and velocity (assuming a layered earth). The actual function used is $1/(\text{time} \times \text{velocity})^2$. The velocity function is input using an editor, so that it may be varied to suit the area. To choose between these two options, see Newman (1973).

"Trace Muting" has three different types of mute available: top, surgical and bottom. While only one type of mute can be specified per call to this module, many mutes may appear in any one processing flow. All data samples that are muted are set to zero. A mute ramp is also provided to smooth the transition from live data to muted data samples. Ramping is done to prevent undesirable side effects from the mute process, especially following the application of filters. The trace mute file is created interactively on the "Screen Display" of the data and is then retrieved from the database when it is to be applied during the processing flow.

Figure 3.4 shows the results of this procedure with the 85 shot gather.

3.1.4 Prefilter (25 Hz high pass filter)

A prefilter is needed to remove the effects of ground roll at shot 85 (Fig. 3.4). Since ground roll is characterised by low frequency and strong amplitude, a high pass filter was applied.

The process applies a frequency filter to each trace that is input. Filters are four-frequency Ormsby or Butterworth (low frequency-low slope-high frequency-high slope) and may be zero phase or minimum phase. In my processing, a single bandpass filter was chose and four "corner" frequencies (20-30-500-500) were specified for the standard bandpass filter. The four values represent sequentially the 0% and 100% points of the low-

32
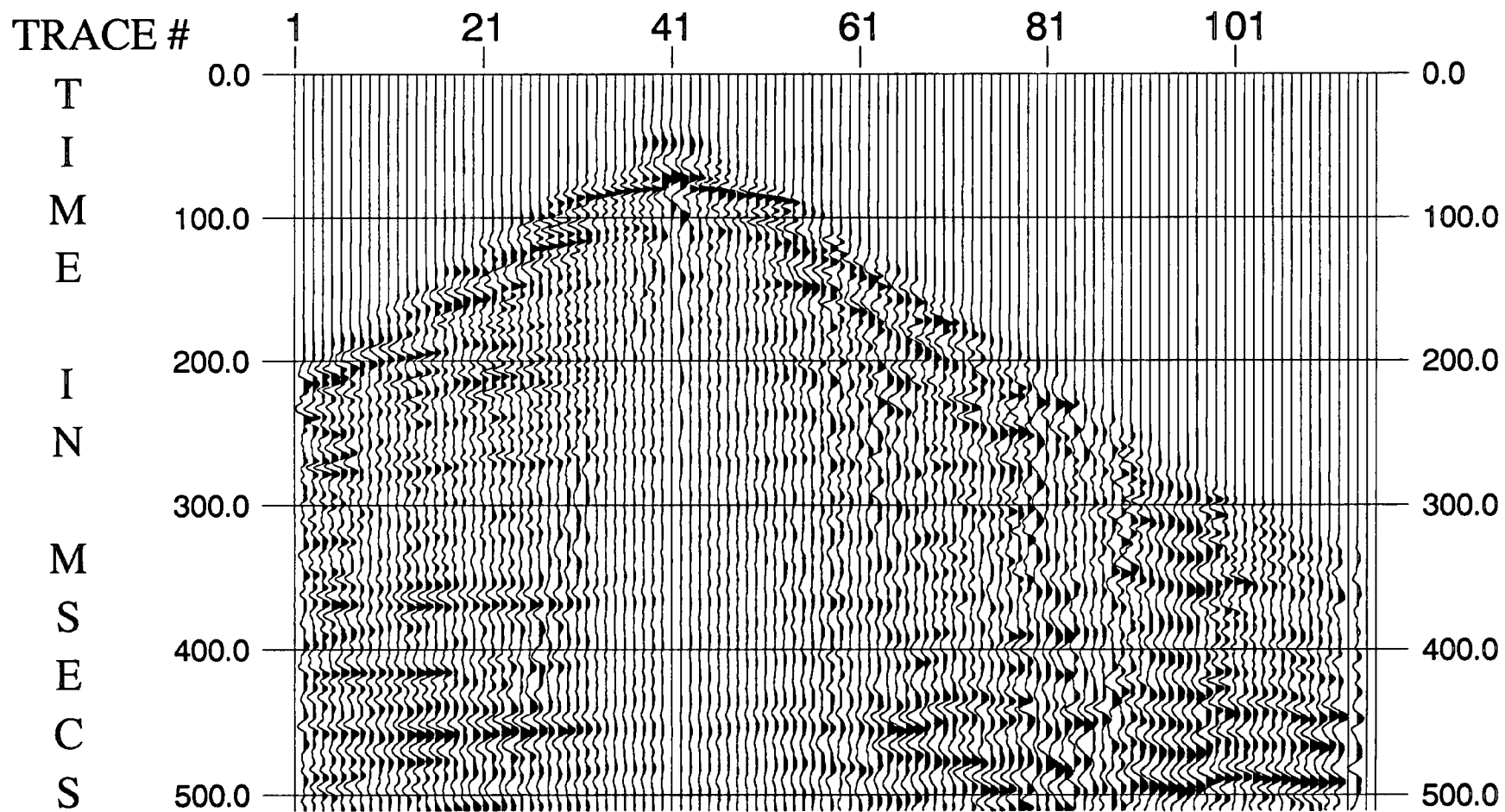
Figure 3.5 The same dataset as Fig. 3.4 with pre-filter applied.
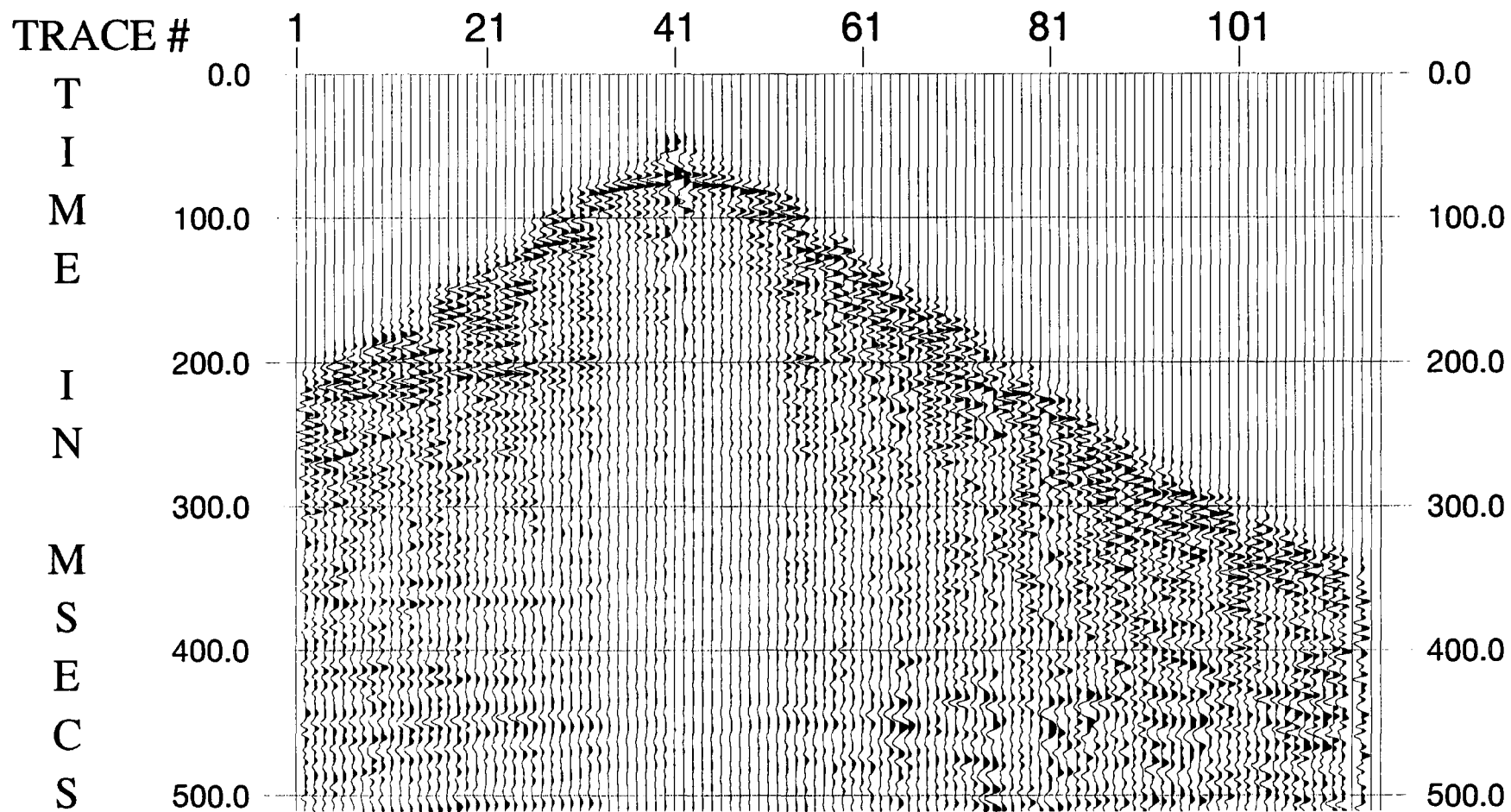
Figure 3.6 The same dataset as Fig. 3.5 with deconvolution applied.

cut ramp, and the 100% and 0% points of the high-cut ramp (in Hz). These ramps are formed by Hanning (cosine) tapers in the frequency domain. Figure 3.5 shows the results after applying the prefilter to the same shot point gather as Fig. 3.4.

3.1.5 Deconvolution

Prestack deconvolution is aimed at improving temporal resolution either by compressing the effective source wavelet to a spike (spiking deconvolution) or, less ambitiously, by truncating it (gapped or predictive deconvolution) (Robinson and Treitel, 1980).

ProMAX has a "Decon Parameter Stack Test" which creates multiple CDP stacks with user-specified pre-stack deconvolution applied, plus one stack with no deconvolution applied as a control. This was used to choose the optimum parameters: operator lengths, prediction distances and white noise levels can be varied.

Then "Ensemble Deconvolution" was used to compute a single deconvolution operator for all of the traces in the input ensemble. This ensemble could be a shot record (in my case), or a CDP or receiver gather. Minimum phase spiking was used for the pre-stack deconvolution. The operator length was 51 samples and the design gate was from 70 ms to 700 ms for zero offset and from 400 ms to 700 ms for 580 m offset. Since spiking deconvolution broadens the spectrum of seismic data, traces contain much more high-frequency energy after deconvolution. Because both high-frequency noise and signal are boosted, the data need filtering with a wide band-pass filter after deconvolution. The bandwidth was 20-30-200-250 Hz.

Figure 3.6 shows the result of deconvolution for the field record acquired at the same shot gather as above.

3.1.6 Field Static Corrections

In order to obtain a seismic section which shows seismic reflectors representing the actual geological structure, the reflection times must be reduced to a defined reference time. This is normally taken to correspond to a horizontal plane fixed at a certain known elevation above mean sea level. The static correction is essentially a time shift applied to each trace to reduce the observed reflection time to the datum plane.

The value of the total static correction depends on the following factors: (1) the perpendicular distance of the source from the datum plane; (2) the surface topography, i.e. the perpendicular distance of the detector from the datum; (3) the velocity variation of the surface layer along the seismic line; and (4) the thickness variation of the surface layer.

Field statics were provided by British Coal, so in ProMAX either "User-defined Statics", which gets the input from the geometry specification, or "Hand Statics", which gets the input from the flow input, can be used to apply them.

Though I have tried many times, "User-defined Statics" still will not work properly, which I suspect is due to bug in the ProMAX system. Eventually, I found I could apply the field statics using "Hand Statics", provided that "Elevation Statics" was applied first. Even though the values of the elevation statics were zero, they were required to create headers for "Hand Statics".

3.1.7 Interactive Velocity Analysis (IVA)

In addition to providing an improved SNR, multifold coverage yields velocity information about the subsurface. Velocity analysis is performed on selected CDP gathers or groups of gathers. The output from each velocity analysis is a table of numbers as a

34
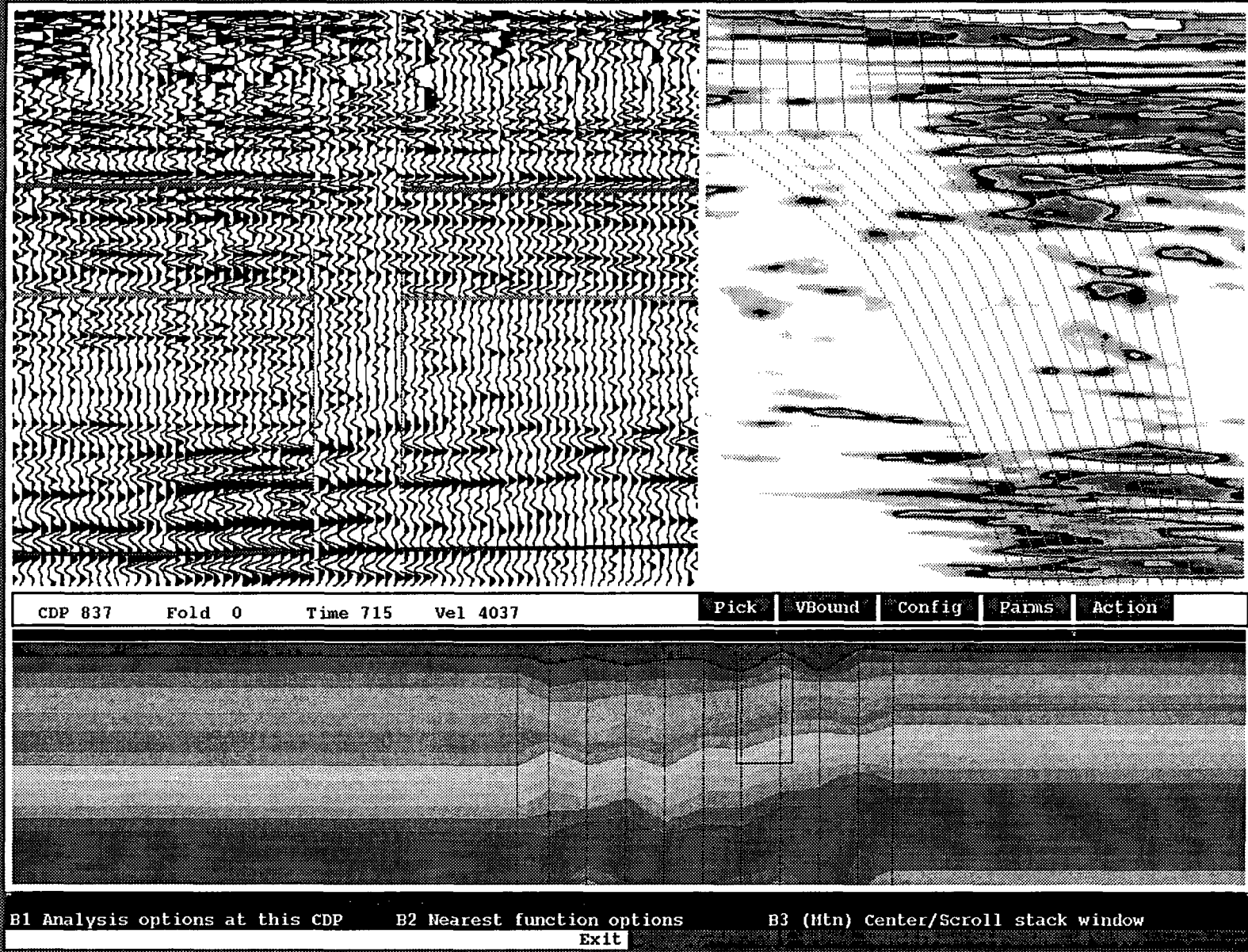
Figure 3.7 Fully interactive velocity analysis displays.

function of velocity versus two way zero-offset time. These numbers represent some measure of signal coherency along hyperbolic trajectories governed by velocity, offset, and travel time.

The "Interactive Velocity Analysis" tool in ProMAX provides comprehensive interactive velocity analysis, velocity quality control, velocity field modification capabilities, mute analysis, and autostatics-compatible horizon picking. In my processing, the "Fully Interactive" option was used. In this mode, the screen is divided into three windows: the upper left hand corner is a stack display; the upper right hand corner is a semblance display; and across the bottom is an iso-velocity contour display. Therefore one can decide which stacking velocity is suitable for the CDP according to all three displays (Fig. 3.7). At the same time, choosing "Yes" for "Provide Horizon Data Table" allows us to select an autostatics-compatible horizon table for the next processing stage.

3.1.8 NMO Corrections and Autostatics

Normal moveout corrections are applied according to the following formula:

$$T_x = \sqrt{T_0^2 + (X/V)^2} \qquad (3.1)$$

where T_x is the actual reflection time of the seismic event; T_0 is the zero offset reflection time of the seismic event; X is the actual source-receiver offset distance and V is the NMO or stacking velocity for this reflection event (Sheriff and Geldart, 1983).

This process applies NMO corrections from a space-variant velocity field. Velocities are interpolated for each CDP. In addition, "Direction for NMO Application" specifies whether to apply the correction for normal moveout (FORWARD), or to remove a previously applied correction (INVERSE) which makes it possible to repeat the velocity analysis and autostatics processes. The stretch mute percentage was set to 30.0. The
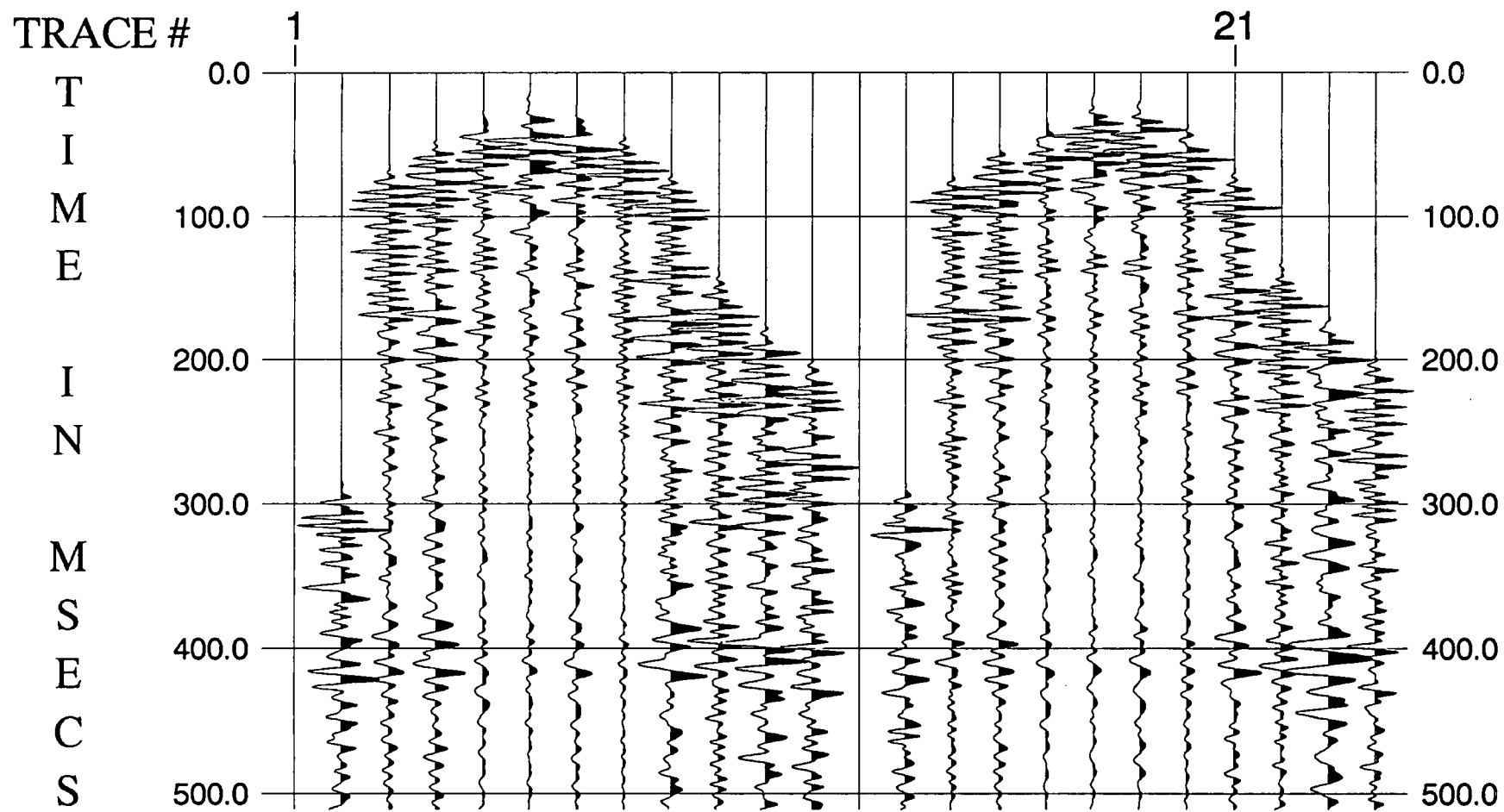
Figure 3.8 CDP gathers 999 and 1000: **(a)** without NMO corrections.

TRACE #

1   21

T
I
M
E

I
N

M
S
E
C
S

0.0
100.0
200.0
300.0
400.0
500.0
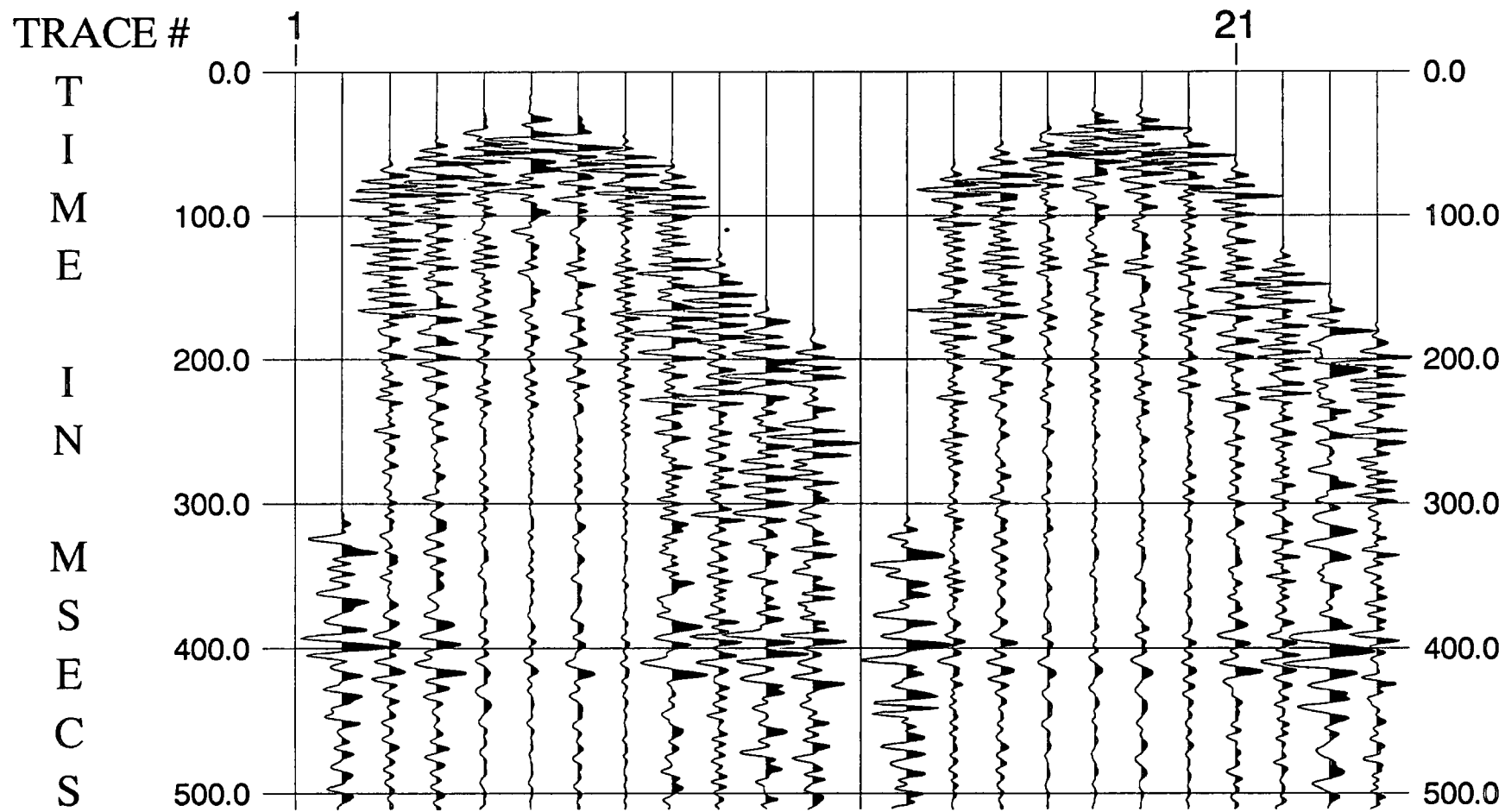
Figure 3.8 CDP gathers 999 and 1000: **(b)** with NMO corrections applied.
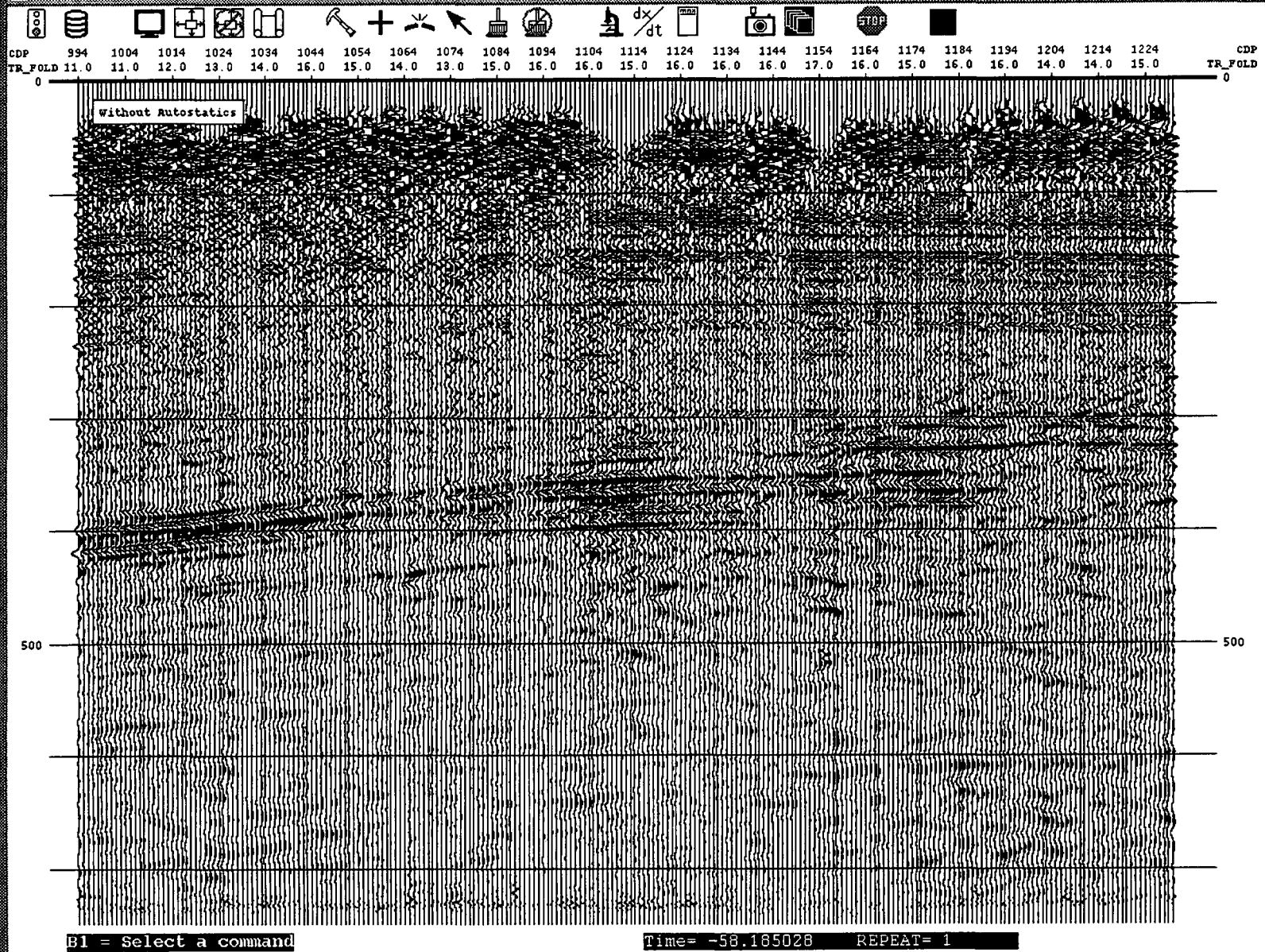
Figure 3.9 Comparison of the stack: **(a)** without autostatics.
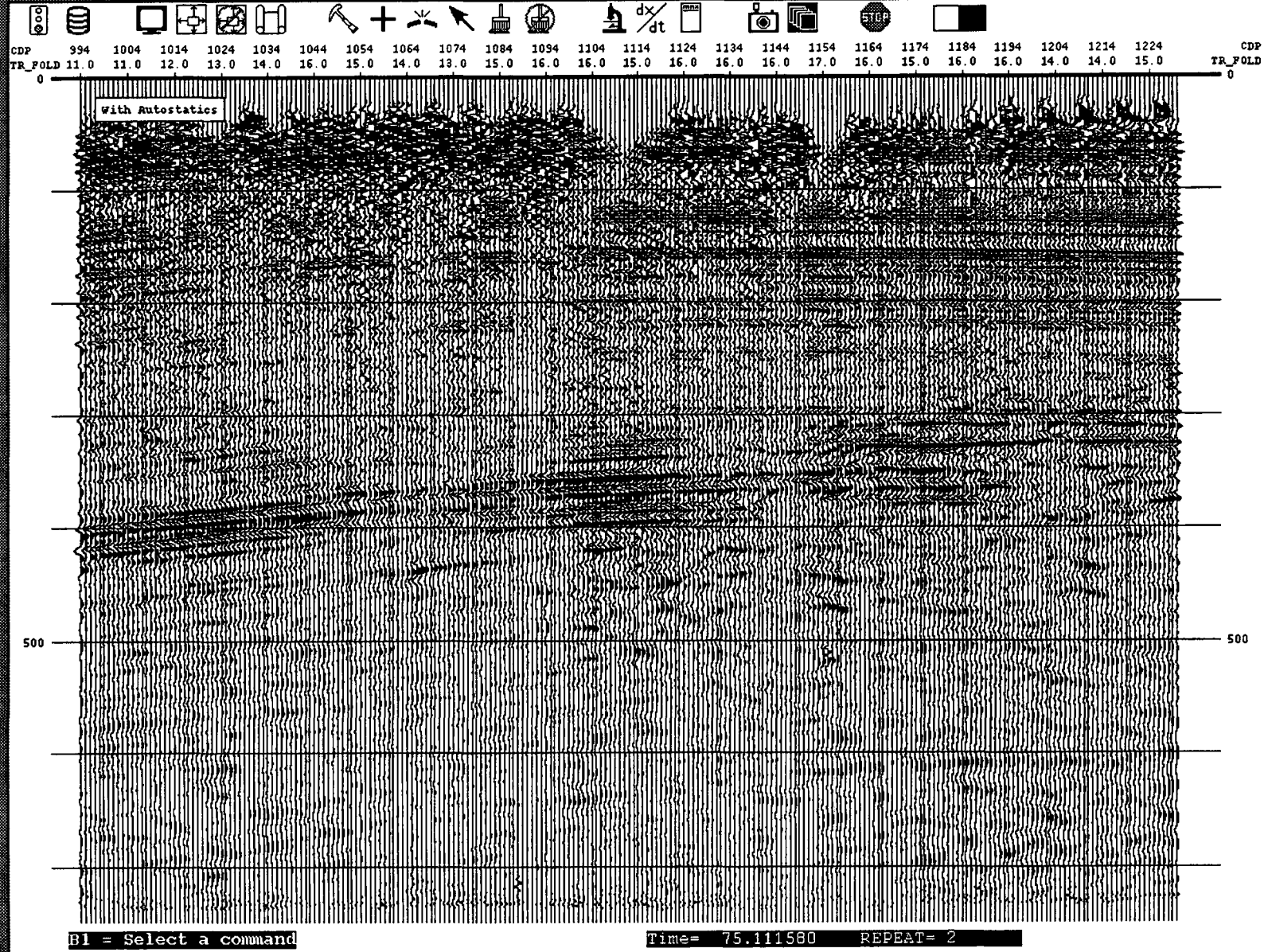
Figure 3.9 Comparison of the stack: **(b)** with autostatics applied.

comparision of NMO corrections applied between CDPs 999-1000 are shown in Fig. 3.8a (before) and Fig. 3.8b (after).

Reflection times are commonly affected by irregularities in the near-surface. To improve stacking quality, residual statics (autostatics) corrections are needed on the moveout-corrected CDP gathers. This is done in a surface-consistent manner; i.e. time shifts are dependent only on shot and receiver locations, not on the raypaths from shots to receivers. The estimated residual corrections are applied to the original CDP gathers with no NMO corrections applied. Velocity analysis may then be repeated to improve the velocity picks.

There are currently five automatic statics options available in ProMAX. All of these, except "CDP Correlation Trim Statics", are surface-consistent solutions: "Maximum Power Autostatics", "Model-Based Correlation Autostatics", "Differential Autostatics", and "Summed Differential Autostatics". The Model-Based Correlation Autostatics was applied to the data in my case. This process measures time shifts relative to a model, and uses a modified Gauss-Seidel method to partition these time shifts into source and receiver statics. It also performs a horizon velocity analysis as part of the estimation of the residual NMO term, and writes these results to the database. The method is relatively insensitive to moderate velocity errors in good quality data (Wiggins et al., 1976).

The maximum static shift allowed was set to 4 ms. The "Compare Autostatics Stack" MACRO process was used to demonstrate the improvement due to autostatics by creating two CDP stacks, one without (Fig. 3.9a) and one with (Fig. 3.9b) autostatics applied.

3.1.9 Constant Velocity Stacking (CVS)

The method of "Constant Velocity Stacking" of certain CDP gathers is an alternative technique for velocity analysis. The most important reason for obtaining a reliable velocity function is to get the best quality stack of signal. Therefore, stacking velocities are often

estimated from data stacked with a range of constant velocities on the basis of stacked event amplitude and continuity.

This 'process' is actually a macro consisting of following process:

Apply AGC (optional)

Constant Velocity Stacks

Screen Display (for the user to pick the CVS panel)

The velocity input option was chosen as "Calculated" for creating stack panels. This "Calculated" option results in a set of velocities which are sampled more finely at low velocities in order to give approximately equal increments in NMO.

After CVS, the "Model-Based Correlation Autostatics" process was applied again using this new velocity table to improve the SNR.

3.1.10 Trim Statics

After all efforts have been made to obtain the optimum statics and velocity solutions, it is a good idea to perform a final pass of non-surface-consistent CDP trim statics. Trim statics are used to optimize trace alignment within a CDP gather. The traces within a CDP gather are cross-correlated against a smoothed version of the corresponding stacked trace. The cross-correlations are used to pick time shifts which will best align the CDP gather traces with the reference stacked trace.

ProMAX provides this tool which computes these trace-by-trace trim statics and loads their values into the database. The resulting statics can be loaded from the database into the trace headers and applied before CDP stacking. To do this, use the "Database/Header Transfer Tool", followed by the "Header Statics Tool".
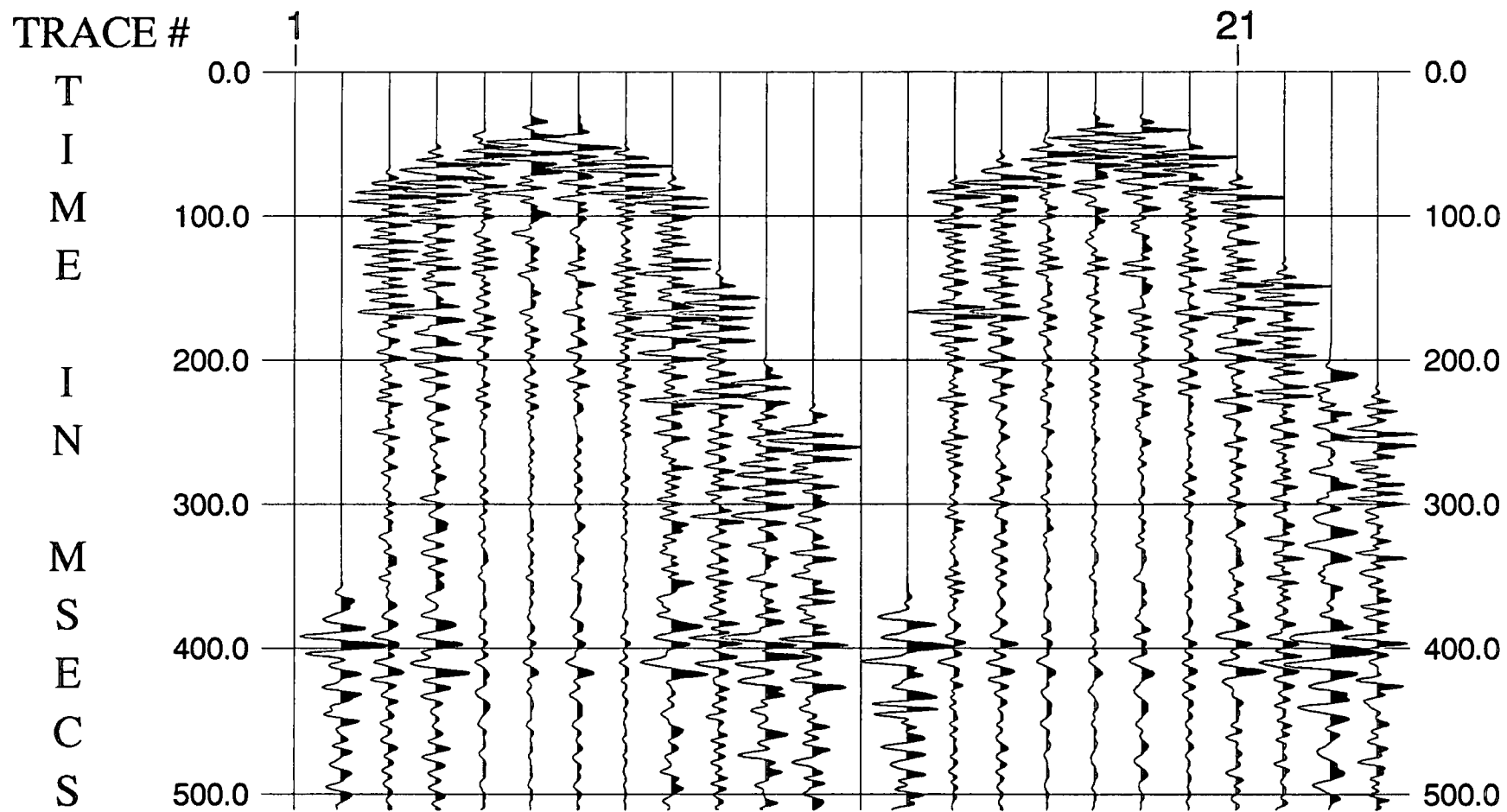
Figure 3.10 CDP gathers 999-1000: **(a)** without trim statics.
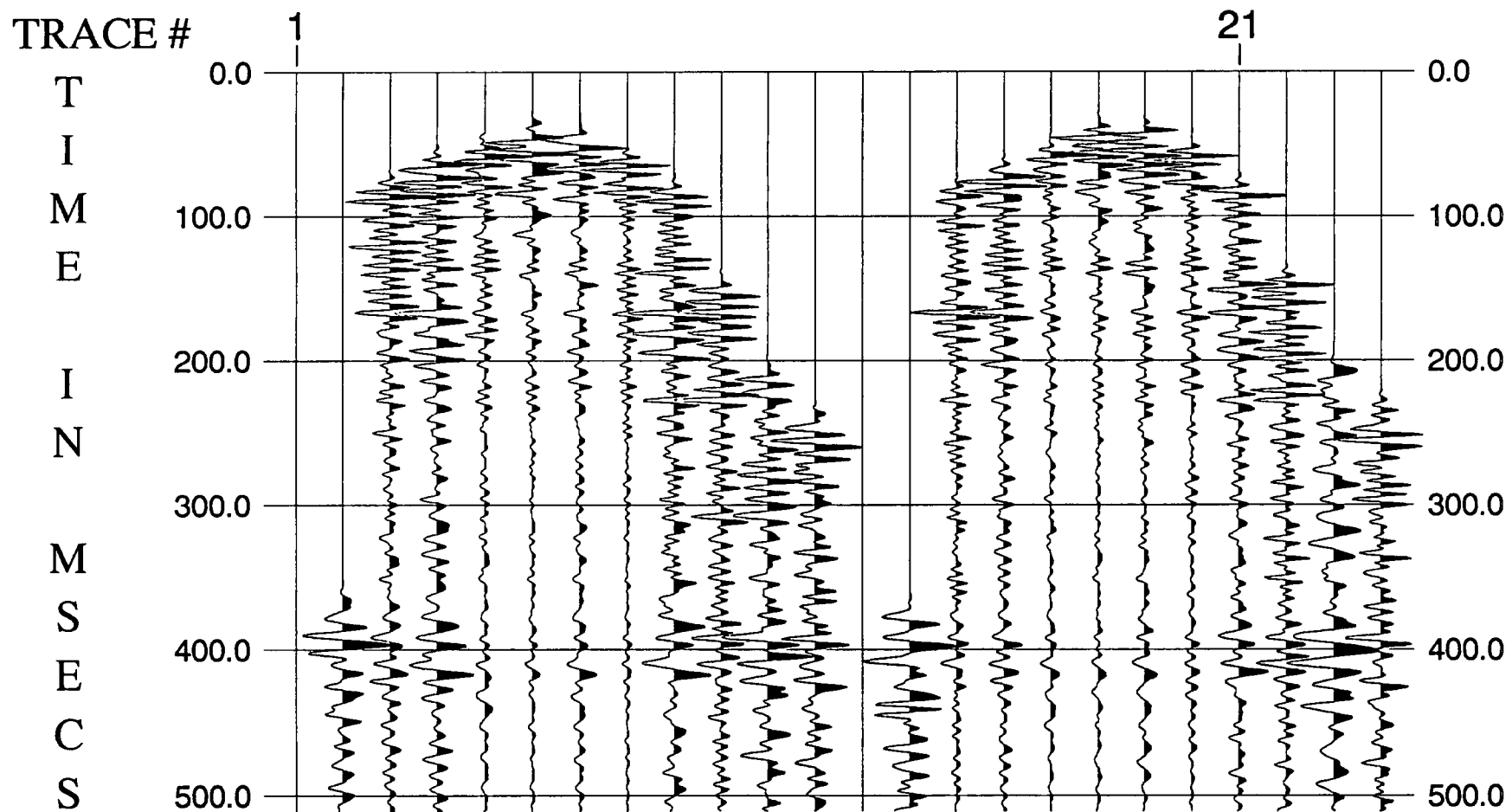
Figure 3.10 CDP gathers 999-1000: **(b)** with trim statics applied.

The maximum static shift allowed was set to 4 ms and a horizon file was generated from IVA process. It was found that trim statics performed better if the process was applied twice, rather than only once, judging by the stacking results. Figures 3.10a (without trim statics) and 3.10b (with trim statics) show the comparision. IVA was carried out for a second time in order to get an up-to-date horizon table between the two applications of trim statics.

3.1.11 Stacking, Trace Equalization and Filtering

In order to get a better quality of stack, a trace equalization was applied to the traces in each CDP gather. This means that all the traces contribute equally in a CDP gather. The details of this process will be discussed later.

The "CDP/Ensemble Stack" process vertically stacks input ensembles of traces. Vertical stack algorithms include: (1) straight mean; (2) header value weighted; (3) sign bit stack; (4) minimum/maximum; (5) sample value exclusion stack; (6) diversity sum; (7) median and (8) alpha-trimmed mean.

The straight mean stack was applied, which sums the sample values and divides by the number of samples summed raised to a user-supplied power. The value of 0.5 was normally chosen to scale by the square root of the number of samples.

This time a Butterworth bandpass filter (Oppenheim and Schafer, 1975) was used in which low frequency, low slope, high frequency and high slope was specified. The Butterworth ramps defined in the frequency domain are formed by

$$R = 1 \Big/ \sqrt{1 + (F/FMID)^{2P}} \qquad\qquad (3.2)$$

38
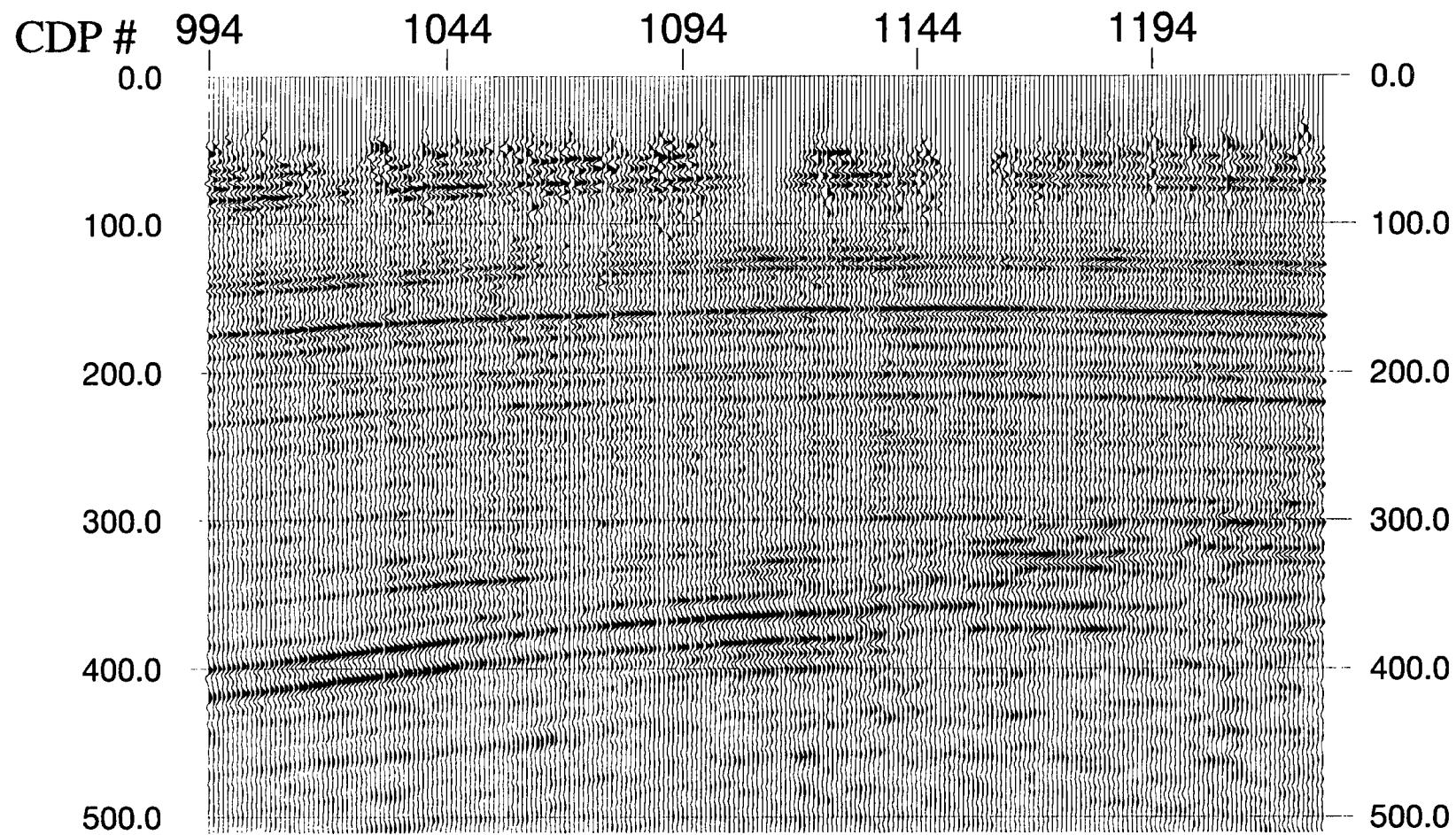
Figure 3.11 Stacked section with all above procedures carried out.

where FMID is the centre frequency of the pass band and P is computed for the lower and upper slopes to get the correct db/octave rolloff. The parameters were chosen as: low cut - 30 Hz, 10 db/octave; high cut - 200 Hz, 20 db/octave. A Butterworth bandpass filter was chosen to match British Coal's processing in order to make a fair comparison. However, the lower and upper slopes are different (See Fig. 3.2).

For the purpose of the later inversion, "Trace Equalization" was performed here. This is a trace-to-trace amplitude balancing function. This program uses a single time window for each trace, which may be spatially varied by a primary and a secondary key. The amplitude in the window is computed, and a scalar calculated to convert this amplitude to a constant value. This scalar is then applied to the entire trace. In this way, variations in amplitude between traces are reduced.

The time gate parameter was set as 851:70-500/1350:60-500/ which means that at CDP 851 the time gate was between 70 ms and 500 ms, and at CDP 1350 the time gate was between 60 ms and 500 ms. The parameters were interpolated for other CDPs between these two. The result of this processing is shown in Fig. 3.11.

It should be pointed that in the British Coal's processing of the data, the time-variant digital bandpass filter and time-variant trace equalization applied at this stage in processing were different from the time-invariant one applied here.

3.1.12 F-K Analysis and F-K Filtering

Multichannel processes can be useful in discriminating against noise and enhancing signal on the basis of a criterion that can be distinguished from trace to trace, such as dip or moveout. The 2-D Fourier transform is a basis for both analysis and implementation of multi-channel processes.
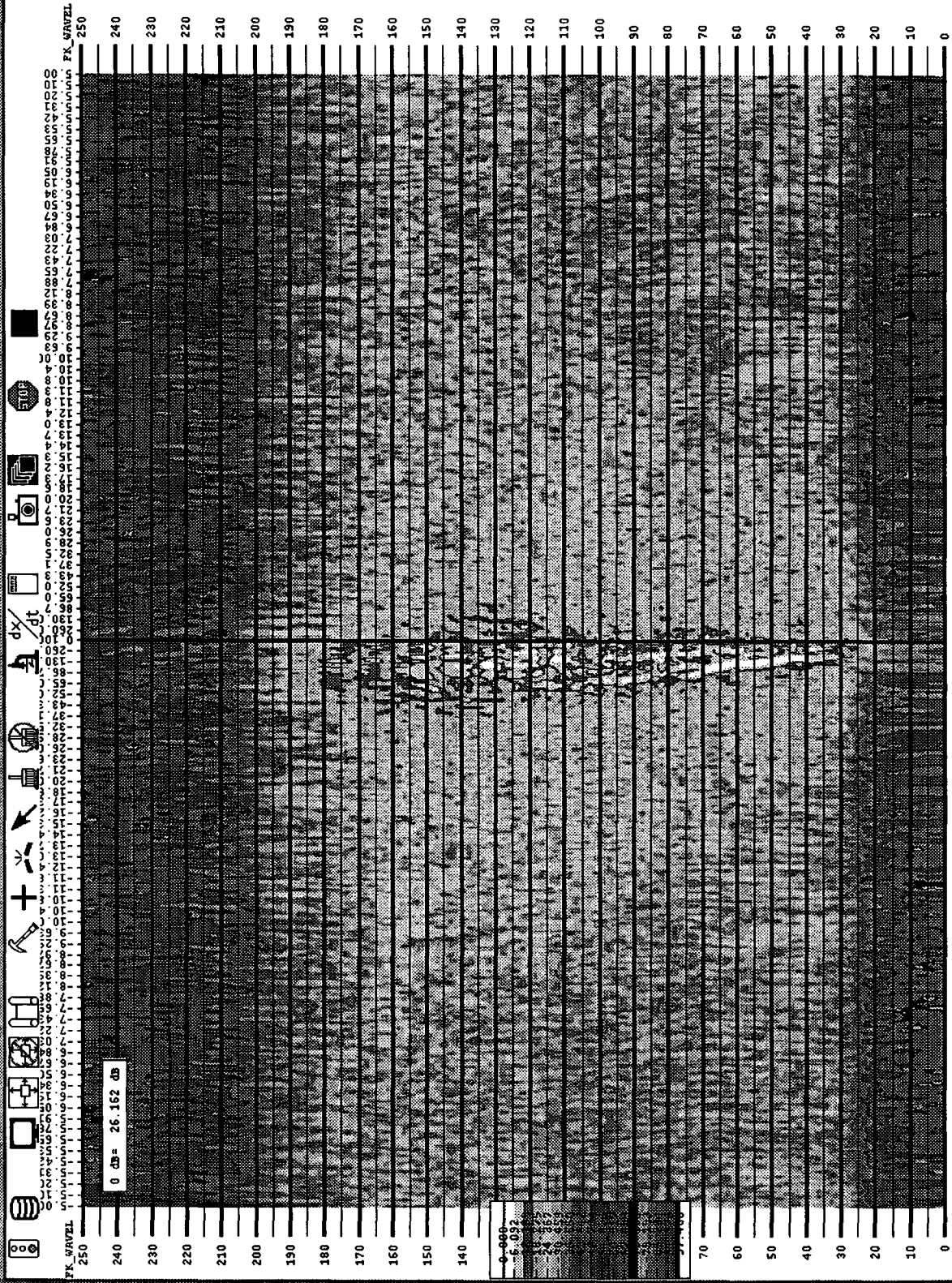
Figure 3.12 F-K analysis for picking of F-K filter polygons.
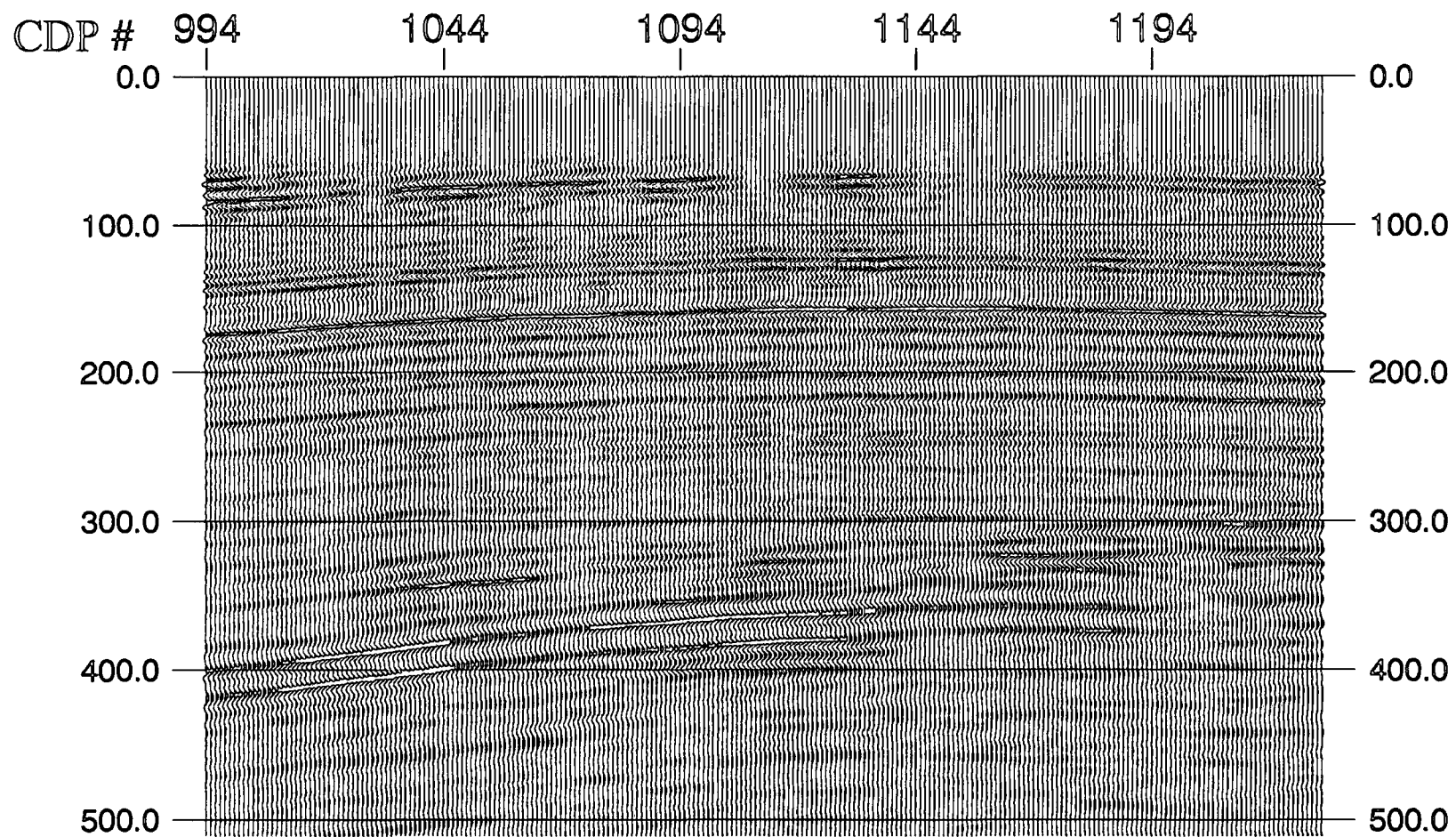
Figure 3.13 The stacked section with F-K filter applied.

Events that dip in the (t,x) plane can be separated in the (f,k) plane by their dips. This allows us to eliminate certain types of unwanted energy from the data. In particular, coherent linear noise (in the form of ground roll), guided waves, and side-scattered energy commonly obscure the genuine reflections that may be present in recorded data. These types of noise usually are isolated from the reflection energy in (f,k) space (Yilmaz, 1987).

Before F-K filtering, the "F-K Analysis" was run. This transforms the data from time and space (t,x) sample values to frequency and wavenumber (f,k) values and displays the results. The displays supported interactive picking of F-K filter polygons (Fig. 3.12).

For F-K filtering, the fan or pie-slice filters are specified by frequency and velocity limits. The program allows data to be passed or rejected within the selected windows. The maximum attenuation and the portion of the zone to be passed at 100% are also under user control. The parameters I chose are: (1) Type of filter: fan filter; (2) Panel width in traces: 256; (3) Fan filter parameters: -2500,4000,30,200 (velocity1-velocity2-frequency1-frequency2); (4) Mode of filter operation: accept; (5) Percent flat for accept zones: 90; (6) Minimum filter attenuation level: 0.001.

The result of the F-K filter is shown in Fig. 3.13. Comparing with Fig. 3.11, it is easy to see that the noise appearing between 250 and 350 ms on the right hand of the section is completely removed from the section.

3.1.13 Migration

Migration is the process of converting the seismic response on stacked sections into its true structure; diffractions are migrated back to their diffraction points at faults, multibranch reflections are migrated into their true synclinal shapes, anticlines are slimmed down, and apparent dips are converted to true dips. For 2D data, migration can only work
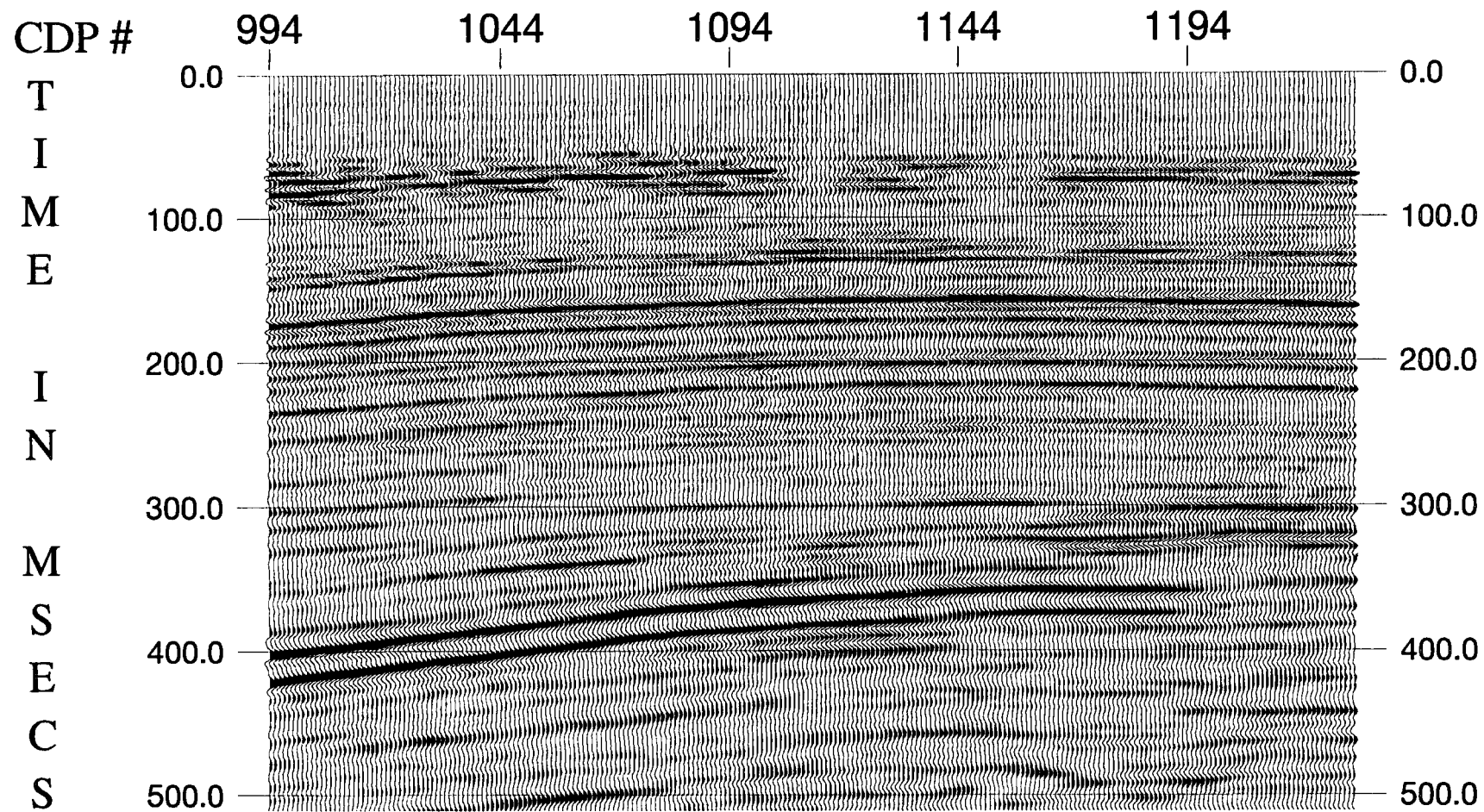
Figure 3.14 The migrated section reprocessed with ProMAX.

correctly if the line is oriented in the dip direction. Otherwise out-of-plane events will be present on the section.

Since the formal solution of the acoustic wave equation in inhomogeneous media is generally an impossibility, resort has been made to numerical methods. In particular, these methods may be based on calculation of finite differences, and "Steep Dip FD Time Migration" was chose for the processing. This process performed a post-stack time migration on an input stack section using a finite difference algorithm capable of improved accuracy at steep dips. The migration algorithm is implemented in the frequency-space domain, i.e. (f,x,z), requiring that the input stacked section be transformed from time to frequency (Claerbout, 1985).

The parameters were set as: (1) Minimum frequency to migrate (in Hz): 30; (2) Maximum frequency vs. depth to migrate: 0-200,2000-160 (Depth1-Max. Frequency1, Depth2-Max. Frequency2); (3) Percent velocity scale factor: 50; (4) Time attenuation factor (dB/sec): 0.2; (5) Largest angle to be properly migrated: 65 (migrated to 65 degrees).

Figure 3.14 showed the migrated section. Comparing Figs 3.1 and 3.14, the differences between the data processed by British Coal and the reprocessed data can be seen.

Firstly, there are some obvious differences in the shallow area. In my reprocessed section, there are no reflections above 50 ms, whereas British Coal's section contains some strong reflections there, and the continuity of the events above 100 ms is not as good as British Coal's. I found that these differences resulted from the different filters applied in the processing flows. Because a time variant bandpass filter was applied in British Coal's processing, the bandpass between 0 and 200 ms is 60 - 200 Hz whereas mine is 30 - 200 Hz along the whole trace. I have found by testing that if the lowcut frequency is increased, the shallow data in my reprocessed section do look more similar to British Coal's section.

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However, the continuity of the target coal seams between 300 ms and 440 ms was worse than Fig. 3.14. Therefore, the bandpass of 30 - 200 Hz was preferred.

Secondly, the SNR of whole section is improved due to the carefully repeated velocity analysis and autostatics. This will be discussed later in Chapter 5 where the improvement is demonstrated by comparing their correlation coefficients with the well log.

Finally, the continuity of the two main coal seams, at 400 ms and 420 ms at CDP 994, in my reprocessed data are better than British Coal's, especially between CDP 1175 and CDP 1196. This will be helpful for the inversion.

3.2 Use of Logging and Coring Information

3.2.1 Introduction

As is generally known, most formations are altered when a borehole is drilled through them. The more competent formations show an imperceptible change, while the softer formations often suffer significant, obvious alterations. Everyone who has worked quantitatively with well logs recognizes that it is not uncommon for portions of a well log to contain data that may be significantly different from the true, in situ formation properties. This may be due to either log calibration problems or environmental conditions.

Ausburn (1977) suggested that one should use three different levels of log editing, which he called mechanical, interpretative and modelling. These log editing methods should be carried out before time-depth reconciliation.

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THORNY PLANTATION
SURFACE BOREHOLE

*SEAM ANALYSED STRATIGRAPHIC HORIZON	DEPTH (metres)	LITHOLOGY	FAUNA / FLORA	STRATA DESCRIPTION	SEAM DETAILS (cm)	CORE DIP	TRUE DIP Dip Azm	GEOPHYSICAL LOG	DRILLING FORMAT	CASING IN HOLE
Clay Cross •JOAN Lower Cwml	500			lt fe /lt flas Coal /lC 24 at 496.16 llstria	1 5 2					
BROWN RAKE				flas 1C 7 at 504.56						
BLACK RAKE	510			rip tr dr. pyr Ironstone flas 1C 30 at 508.17 1C 24 at 508.57 1C 8 at 510.52 rip tr dr.						
				Coal 1 at 516.35 strong rip						
	520			rip						
•DEEP MAIN	530			1C 5 at 528.82 Coal /1C 258 at 529.51 1C 8 at 529.81 1C 5 at 530.05	2 144 7 44 23 39					
	540			pyr tr dr. rip bioturb lt Pop dunes						
	550			rip bioturb		2°				
•PARKGATE/TUPTON				pyr	40 8 38 15					
THREEQUARTERS	560			Coal 331 at 559.08 Lost Core lt 1C 43 at 560.80	107 4 119					
				pyr						
	570									
•YARD •YARD FLOOR COAL				lt Coal /1C Coal 29 at 573.93 at 574.18	12 31 33 25					

Figure 3.17 Lithology profile (part) of Thorny Plantation borehole.

PILL BOX No.1

Surface Borehole

•SEAM ANALYSED STRATIGRAPHIC HORIZON	DEPTH (metres)	LITHOLOGY	FAUNA / FLORA	STRATA DESCRIPTION	SEAM DETAILS (cm)	CORE DIP	TRUE DIP Dip Azm	GEOPHYSICAL LOG	DRILLING FORMAT	CASING IN HOLE

Clay Cross JOAN

BROWN RAKE

BLACK RAKE

•DEEP MAIN

•PARKGATE / TUPTON

•THREEQUARTERS

YARD
YARD FC

460
470
480
490
500
510
520
530
540

rip
Ironstone
tr pyr
Coal   42 at 467.71
listric Coal   48 at 469.92
Ironstone lt
Coal   22 at 472.42
Coal   70 at 473.39
tr dr.
rip
Coal 264 at 480.85
IC   at 481.47
pyr
ll floo
Coal 132 at 517.15
Coal IC
      45 at 518.32
bioturb tr floo
Coal 78 at 530.52 lt
IC   18 at 531.41
bioturb

Figure 3.18 Lithology profile (part) of Pillbox borehole.

Figure 3.19 Edited sonic log at Thorny Plantation borehole.

Edited Sonic Log at TP Borehole
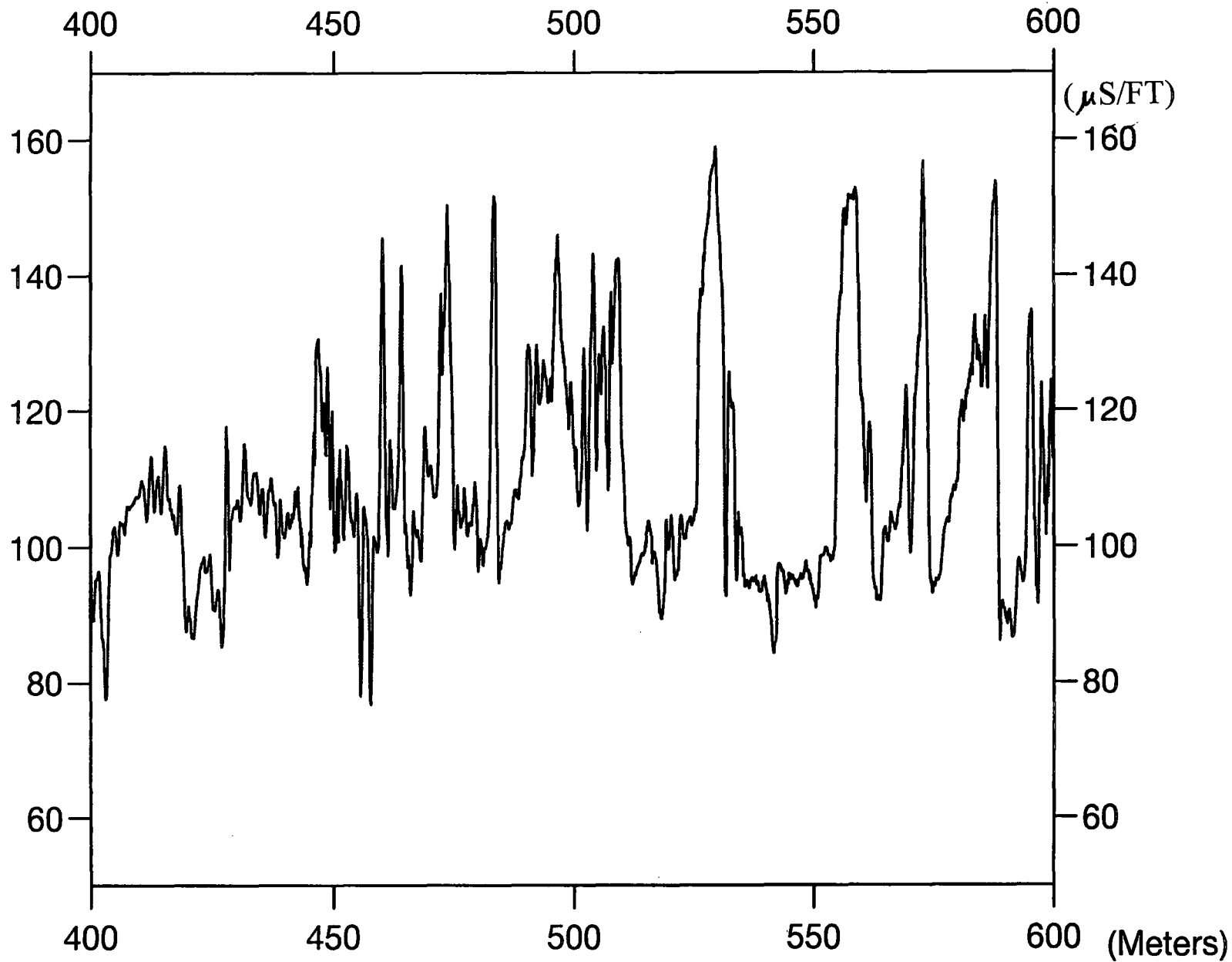
Figure 3.20 Acoustic impedance plotted against two-way travel time at Thorny Plantation.
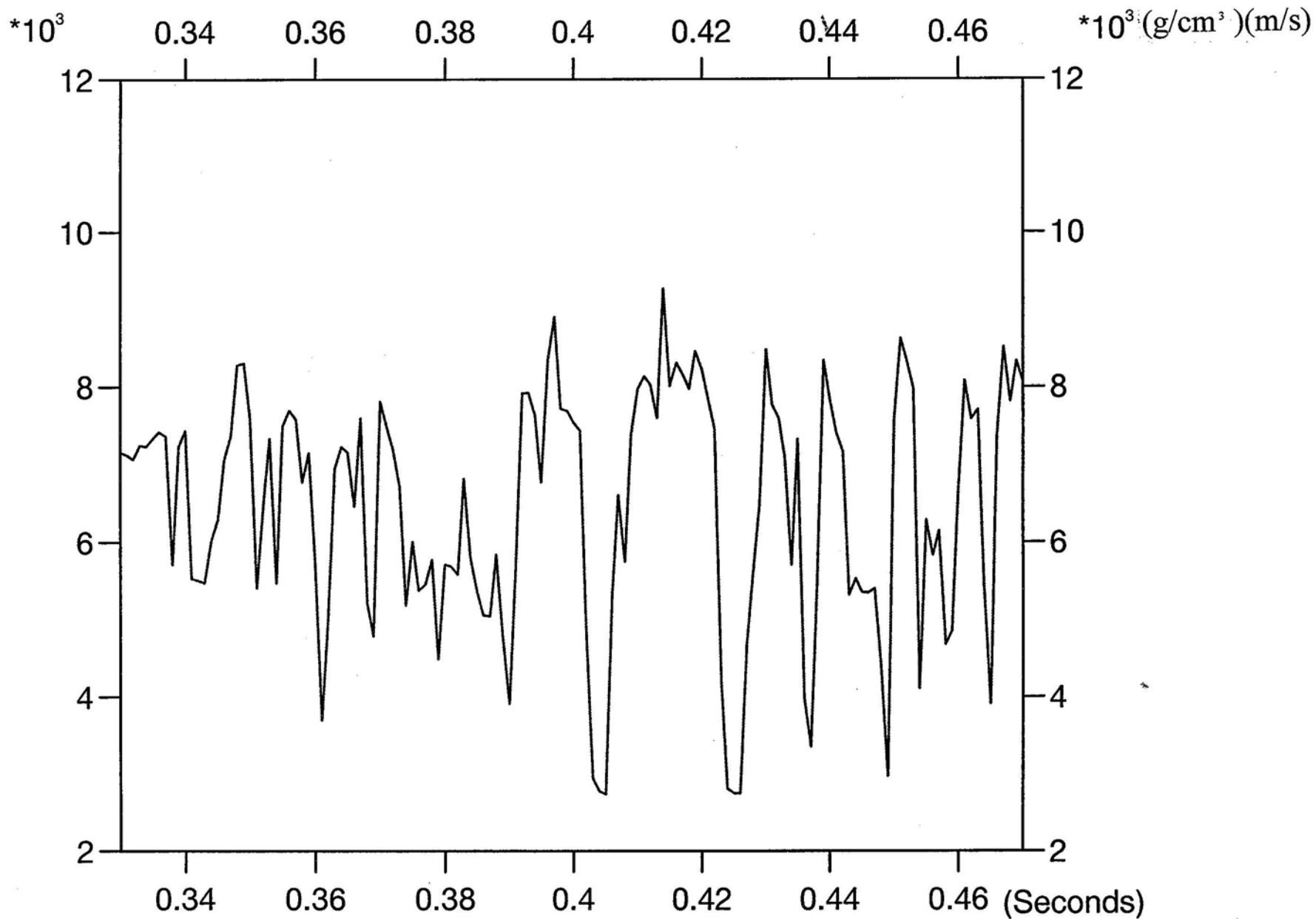
3.2.2 Mechanical Log Editing

Due to the compensated sidewall tool used for the density log, the calibration error was supposed to be negligible. Therefore mechanical editing included the detection of obvious instrument/electronic noise (cycle skipping and so on) in the sonic log from Thorny Plantation (at 515 m and 540 m on Fig. 3.15) and obvious hole-related errors from Pillbox (at about 500 m on Fig. 3.16).

3.2.3 Interpretative Well Log Editing

This type of editing included making judgements in both recognizing bad data values and in substituting better ones. Because the lithologies from coring information (Fig. 3.17 for Thorny Plantation and Fig. 3.18 for Pillbox), and other logs are available (neutron and gamma, etc.), it is not too difficult to identify the lithology and estimate corresponding sonic or density values. Figure 3.19 shows the edited sonic log data from Thorny Plantation. Some smoothing was also applied in this process based on interpretative judgement using the other available information.

3.2.4 Modelling Well Log Editing

After the above two editing procedures, the forward model (seismic response) based on the edited acoustic impedance to compare with the observed data (seismic information) can be calculated. It can be shown whether the editing has improved the correlation or not by using the correlation coefficient defined by equation (2.2$\overset{2}{0}$). If the edited model produces a better result, it is accepted; otherwise some further editing is required. For example, there are some very high sonic values giving the appearance of a thick coal seam at about 490 m depth on the well log at Thorny Plantation borehole (Fig. 3.15), but on the lithology profile at the corresponding depth there is only a thin (0.24 m) coal seam (Fig.

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Acous. Imp. in Two-way Time at PB
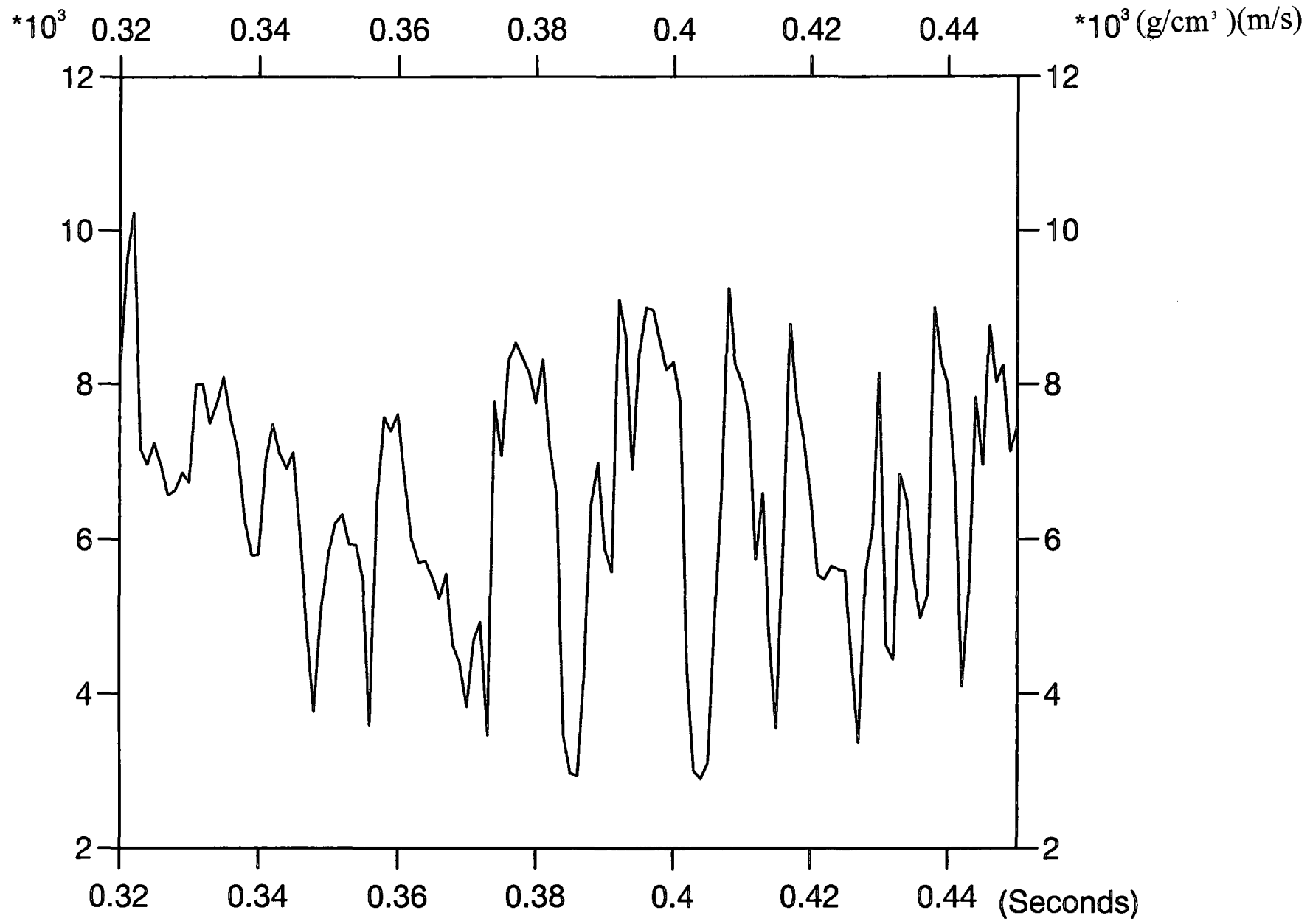
3.17). I corrected these high values to the same lower values as the surrounding rocks. The corrections were accepted because the correlation coefficient is increased following corrections.

This so-called modelling method is totally different from Ausburn's (1977). He used either theoretical relationships or empirical observations of the saturated rocks to calculate the formation density and wave velocity. In my editing, the values of real density and velocity are more important than knowing precisely the lithological composition. This is because his objective was to interpret the well logs in terms of lithology, whereas I am attempting to invert seismic data.

3.2.5 Depth-Time Reconciliation

In order to get an acoustic impedance log in terms of two-way travel time for the purpose of inversion, a depth-time transformation has to be applied. There is a major difference between this reconciliation and time-depth transformation in seismic reflection interpretation. In the well log, the depth interval is very fine (1 cm), so interpolation is not required. Here the fraction of the depth interval and average value of velocities for the integer sample period should be considered instead. The results are shown in Figs 3.20 (Thorny Plantation) and 3.21 (Pillbox).

3.3 Inversion Procedure

3.3.1 Introduction

In Cooke and Schneider's (1983) GLI method some constraints were required. Firstly, in the initial guess model the location of each boundary must lie within a distance X of the solution. The distance X is defined as one-half of the central lobe width of the source

wavelet (normally less than 4 samples in the time domain). That is difficult to realise for the reflected events in a recorded trace. Secondly, the polarity at each impedance contrast should have the same polarity as the corresponding arrival on the seismic trace to be inverted. This is also not easy to do, especially if there is no prior knowledge about the wavelet. This, in my opinion, directly led to their conclusion that residual wavelet effects are negligible, allowing them to assume a zero-phase wavelet in all cases.

A modified GLI method using a parameterized wavelet as well as a parameterized earth model is developed here to overcome these faults. The initial guess for the model parameters is best obtained using well data, but an alternative method based solely on the seismic trace, which inverts for the reflection coefficient sequence, has also been implemented.

3.3.2 Initial Guess for the Earth Model

After well log editing, I have got the acoustic impedance as a function of two-way travel time. Based on this acoustic impedance information and the post-stack section from field seismic data, an inversion window and the number of layers (blocks) can be selected. Of course, this task is not an easy one and will be discussed in a systematic study of the real dataset in Chapter 5.

Then the initial guess parameters for the earth model can be established. Starting at the top of the model, each layer needs three parameters to describe it: the location of the bottom boundary in two-way travel time τ, the acoustic impedance p at the bottom of the layer, and the gradient of acoustic impedance g. In the jth layer, the acoustic impedance at each sample is given by

$$e_i = p_j + g_j(\tau_j - i) \quad (\tau_{j-1} \le i \le \tau_j). \quad (3.3)$$

According to equation (2.5), the reflection coefficient sequence r in discrete form at each sample is expressed by

$$r_i = \frac{e_{i-1} - e_i}{e_{i-1} + e_i} \qquad (3.4)$$

The first trace to be inverted should be at the nearest CDP to the well on which the guess model is based.

3.3.3 Wavelet Extraction

To solve those problems mentioned in §3.3.1, the first step is to extract a fairly accurate wavelet by applied a Wiener shaping filter (Robinson and Treitel, 1980) using the observed trace and prior knowledge about the acoustic impedance, which in my case comes from the well logs.

The Wiener shaping filter w is the best (m+1)-length filter, in the least-error energy sense, which may be convolved with the (n+1)-length input reflection coefficient sequence r (derived from edited well logs) to match an (m+n+1)-length desired output d, which is the observed trace at the well.

The normal equations are:

$$\sum_{i=0}^{m} w_i a_{j-i} = g_j \qquad (j=0, 1, 2, ..., m), \qquad (3.5)$$

where the unknown w_i are the weighting coefficients of the Wiener shaping filter, the known a_{j-i} are the autocorrelation coefficients of the input r, and the known g_j are the cross-correlation coefficients between the desired output d and the input r. The Levinson recursion was used to solve the normal equations.

In order to get the best filter (wavelet estimate), the desired output had to be shifted to and fro in time. For each time shift, the error energy defined in (2.18) between the actual output and the desired output was calculated. The best filter was chosen according to the minimum error energy and the corresponding time shift was then applied to the observed trace. There are several sources of error contributing to this time shift, some resulting from the fact that the well logs and seismic section are referred to different datum levels. It is assumed that this time shift will be present in all the traces along the section.

3.3.4 Wavelet Parameterization

In my inversion, the wavelet is to be defined by a maximum of eight parameters in the frequency domain (see §2.4). The best-fitting values of these eight parameters need to be found for the wavelet extracted by the Wiener shaping filter. These values then define the initial guess of the wavelet parameters prior to GLI.

The amplitude spectrum $A(f)$ of the extracted wavelet $w(t)$ is studied for obtaining the frequency parameters. If f_{max} is the frequency corresponding to the maximum value A_{max} of amplitude spectrum, then four frequency parameters are defined as follows. First, f_2 is the largest frequency less than f_{max} such that $A(f_2) = 0.8 \, A_{max}$. Secondly, f_3 is the smallest frequency greater than f_{max} such that $A(f_3) = 0.8 \, A_{max}$. Similarly, f_1 is the largest frequency less than f_{max} such that $a(f_1)=0.2 \, A_{max}$; and f_4 is the smallest frequency greater than f_{max} such that $A(f_4) = 0.2 \, A_{max}$.

In order to fit the quadratic polynomial for the phase spectrum given in equation (2.18), it is necessary to unwrap the phase spectrum of the extracted wavelet. This can be done in the frequency domain, as described by Shatilo (1992), using the polynomial fitting technique (User's Manual of NAG Fortran Subroutines).

The initial phase spectrum of the extracted wavelet w(t) may be written as

$$\Phi_{in}(f) = \arctan\{Im[W(f)]/Re[W(f)]\}, \tag{3.6}$$

where W(f) is the complex spectrum of w(t), for $(-\pi/2) \leq \Phi_{in}(f) \leq \pi/2$. Transformation from $\Phi_{in}(f)$ to $\Phi_{pr}(f)$ for $-\pi \leq \Phi_{pr}(f) \leq \pi$ can be done by analysis of the sign combination of Re[W(f)] and Im[W(f)]. $\Phi_{pr}(f)$ is the main (or principal) value of the phase spectrum $\Phi(f)$, given by traditional spectral analysis of the phase spectrum alone. Since the true value of the phase spectrum $\Phi(f)$ lies between $-\infty$ and $+\infty$, $\Phi(f)$ and $\Phi_{pr}(f)$ are related by the expression

$$\Phi(f) = \Phi_{pr}(f) + 2\pi n, \tag{3.7}$$

where n is an integer. The transition from $\Phi_{pr}(f)$ to $\Phi(f)$ is called phase unwrapping (or phase restoration).

Phase unwrapping should remove discontinuities in the phase spectrum $\Phi_{pr}(f)$. Two types of discontinuity have been defined (Poggiagliolmi et al., 1982). The first is a discontinuity of 2π caused by a complex vector transition from one sheet in the Riemann surface to another, and the second is a discontinuity of π at the frequency where the wavelet amplitude spectrum A(f) is equal to zero. The second one does not occur within the signal bandwidth of the extracted wavelet in my examples. Therefore I adopted the phase restoration presented by Shafer (1969), in which he proposed taking the phase increment $\Delta\Phi_{pr}(\Delta f)$ between two adjacent frequency points $\Delta f = f_i - f_{i-1}$

$$\Delta\Phi_{pr}(\Delta f) = |\Phi_{pr}(f_i) - \Phi_{pr}(f_{i-1})|, \tag{3.8}$$

It is assumed that a discontinuity of 2π exists if $\Delta\Phi_{pr}(\Delta f)$ exceeds π. The unwrapping process starts at zero frequency and it is repeated for each consecutive harmonic. And the sign of this 2π is the same as the sign of $\Phi_{pr}(f_i) - \Phi_{pr}(f_{i-1})$.

Then I approximate the phase spectrum as defined in (2.18). Because Φ is known, it is possible to find φ_0, φ_1 and φ_2 by polynomial fitting. In order to get a better match for the wavelet, I fit the phase spectrum only in the range between f_2 and f_3. However, the subroutine E02ACF from the NAG Fortran Library treats f_2 as a coordinate origin in order to get an intersection value with ordinate axis. Therefore a simple transformation of the frequency coordinate (abscissa) is needed. After fitting, the reverse coordinate transformation is carried out.

The wavelet is defined in the frequency domain as

$$W(f)=A(f)\exp[-i\Phi(f)], \qquad\qquad (3.9)$$

where $A(f)$ is the amplitude spectrum to be approximated by the tapered boxcars (Fig. 2.2) defined by four frequency values, f_1, f_2, f_3, f_4, and an amplitude scaling factor. The wavelet has three phase parameters, one amplitude and four frequencies; therefore it is called the 8-parameter wavelet.

Because my program always calculates the forward-modelled trace in the frequency domain, it is easy to apply this 8-parameter wavelet in this domain. However, sometimes if the inversion for the reflection coefficient sequence is used, it is necessary to transform this 8-parameter wavelet into a wavelet of chosen length in the time domain. In my case, it is a 32-length digital wavelet. The inverse Fourier transform and cosine tapers over 5 samples at each end in the time domain are used to get the 32-length wavelet.

3.3.5 Initial Boundary Inversion

The boundary locations must be solved for independently of the impedance because GLI is a procedure that minimizes the error between the observed seismic trace and the synthetic seismic response. If a given boundary has the correct impedance contrast but the wrong location, there are two ways to reduce the error: (1) move the location of the boundary; or (2) change the impedance contrast. The non-linear relationship between boundary locations and seismic response effectively means, as discussed in §2.5, that boundary locations and acoustic impedance values are not independent model parameters. If one tries to invert for these parameters together, each will try to reduce the error energy independently of the other, so the change in model parameters will overshoot instead of finding the minimum. To avoid this, the impedance are solved for only after all the boundary locations are known.

Inversion for the boundary locations therefore has to be done independently of the other model parameters. For the trace closest to the borehole, the first application of GLI is to estimate the boundary locations using the extracted wavelet in the time domain. During this first step, the wavelet was fixed; also the acoustic impedance and their gradients are all fixed at their 'initial guess' values obtained from well log information.

In the inversion, the Jacobian matrix of partial derivatives must be computed. These derivatives can be determined by formal differentiation if the model is simple enough. But where the model parameters do not appear directly in the forward formula due to the discrete parameterization, the partial derivatives may be approximated by finite differences (Lines and Treitel, 1984). This can be computationally expensive since it is necessary to determine the complete model responses for a change in each parameter. Then the simplest finite difference formula is used to approximate the partial derivative by

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$$\frac{\partial F(A)}{\partial A} = \frac{[F(A + \Delta A) - F(A)]}{\Delta A} \tag{3.10}$$

3.3.6 Wavelet Inversion

The initial guess for the 8-parameter wavelet was obtained by fitting a polynomial to the phase spectrum and by making an empirical approximation to the amplitude spectrum. Therefore the next step following the initial inversion for the boundary locations is to invert for the wavelet parameters by GLI before any further inversion for the earth model is carried out. When the unwrapped phase spectrum is close to linear, a 7-parameter wavelet can be defined for inversion, with φ_2 set to be zero. The amplitude of the wavelet scales the forward-modelled trace with the observed trace. The program also has alternative choices for the shape of the amplitude spectrum other than the boxcar-with-cosine-tapers shape.

After this first inversion to optimise the wavelet parameters, one can choose to fix the wavelet for inverting the earth model parameters along the seismic section. This would be logical if one had grounds for believing the effective wavelet in the seismic data is constant (e.g. from consistent wavelet estimates at different boreholes). Otherwise, one can proceed by iteratively inverting for the boundary locations, acoustic impedance values (both the constant values at the top of each layer and the gradient in each layer, simultaneously), and the wavelet parameters.

3.3.7 Boundary Inversion

Previous work (Cooke and Schneider, 1983) has only mentioned that the boundaries should be inverted first because of the interference between the boundary locations and acoustic impedance values. I have found, moreover, that it is better to invert for the wavelet and acoustic impedance parameters separately, which does not cause any significant extra computational cost. One of the reasons is that these different kinds of

parameters have different orders of the optimum damping factors. Another reason is to avoid interference with each other. For instance, the amplitude spectrum of the wavelet obviously affects the amplitude of the forward-modelled trace, but the same effect can be achieved by changing all the acoustic impedance values such that all the reflection coefficients are scaled by the same factor.

The inversion proceeds exactly as in §3.3.5, except that the wavelet is now the 7-parameter or 8-parameter wavelet.

Alternatively, if the previous inversion has become lost (e.g. on meeting a fault), another procedure for obtaining the initial guess instead of using the inversion result from the previous trace is introduced. In this case, my strategy is to take the last reliable estimate of the effective wavelet as a 32-length digital wavelet in the time domain. This wavelet can be an extracted wavelet or a parameterized frequency-domain wavelet which should be first transformed to time domain. The wavelet is fixed and least squares is used to find the reflection coefficient sequence in the time domain which gives the best fit to the observed trace.

This estimated reflection coefficient sequence will, in general, have non-zero values at every sample. In order to proceed using GLI with parameterization, it is necessary to limit the number of non-zero reflection coefficients to some arbitrary number of boundaries chosen for the parameterized acoustic impedance model. The program can automatically locate this arbitrary number of boundaries according to the relative amplitudes in the estimated reflection coefficient sequence. Of course, some constraints should be put on this choice, e.g. maximum difference from the previous boundary location; otherwise another relatively large value will be chosen within this constraint.

Then the acoustic impedance for this new model in every layer are kept the same as for the previous inversion result, although this does require some interpretative judgement on the correlation between layers.

3.3.8 Acoustic Impedance Inversion

Theoretically, it is not difficult to invert for the relative amplitudes of acoustic impedance when the locations of boundaries are correct and the thicknesses of the layers are greater than the dominant wavelength in the data. In order to invert for the true values of acoustic impedance, it is necessary to fix the known acoustic impedance value of at least one layer .

If the acoustic impedance above a boundary is $e_i + \Delta e_i$, and the acoustic impedance under the boundary is $e_i - \Delta e_i$, then according to the equation (3.4), the reflection coefficient is

$$r_i = \frac{\Delta e_i}{e_i} .$$

(3.11)

As long as $\Delta e_i \ll e_i$ for all the interfaces, it can be assumed that the sample values of the synthetic trace are linearly related to the acoustic impedance values.

For the real data from the Belvoir Coalfield, in order to solve the problems, only two lithologies were taken into consideration - coal seams and country rocks (e.g. Dresen and Ruter, 1994). It can be seen from the well logs that the acoustic impedance of coal does not change much along the section, nor even between seams, which makes it reasonable to fix it. For country rocks one has the option to invert for their acoustic impedance or to fix them. In the inversion, maximum and minimum values for the acoustic impedance of the country rocks were set according to the well logs.

Inversion for the gradient of acoustic impedance can be considered as fine tuning of the constant acoustic impedance values found in each layer by the previous procedure. The maximum values for the gradients may be set according to well logs. Inversion of the gradients can be done simultaneously with constant values of acoustic impedance taken at the bottom of each layer.

3.3.9 Inversion of Adjacent Traces

The termination of iterations for optimising wavelet parameters and earth model parameters is determined by one of the following factors:

(1) the error energy between the observed and forward-modelled traces is less than some arbitrary small value;

(2) the current minimum error energy has remained unchanged after successive iterations; or

(3) the number of iterations reaches some arbitrary maximum value.

After completing the inversion process for the starting trace closest to the borehole, the next seismic trace can be inverted either by using the results from the previous trace as the initial guess model or by basing the initial guess on other interpretive information, as will be discussed in Chapter 5. Inversion then proceeds, trace by trace, along the section. The inversion results for each trace and some useful parameters such as the normalized energy value, are saved and therefore the program can be carried on after interruptions, which is very useful for work with a long computation time.

3.3.10 Summary

In general, the boundary locations are the most important parameters to invert in coal exploration because the acoustic impedance of the coal seam is normally stable. The main aim is to determine seam thickness, including the identification of washouts, and also to find any seam splits or small faults. However, boundary locations are the most difficult type of earth model parameter to invert. Furthermore, the wavelet phase parameters and acoustic impedance parameters are all affected by changes in the boundary locations. The difficulties and some methods for resolving them are illustrated on synthetic and real data, respectively, in Chapters 4 and 5.

4 A Synthetic Model

4.1 A 1-D Synthetic Example without Noise

4.1.1 Introduction

Before the field data from British Coal were processed, some tests were carried out on synthetic data in order to prove that the programs are working. The results of the tests also give some indication of potential problems which might arise when inverting real data. First I consider the situation in which the data are noise-free.

Because there is no scaling problem for the synthetic example, the error energy can be used to measure the quality of the match between the synthetic data trace and the forwarded-modelled trace. In the real data case, the correlation coefficient may be used to describe the similarity between the observed data trace and the forward-modelled trace, and the error energy is used as the criterion for the inversion quality.

In the synthetic example, the sampling interval is 1 ms and the length of the wavelet is 32 ms, as they are for the field data described in Chapter 5. The length of the whole trace is 512 ms. The inversion window is set to be between 300 ms and 470 ms. The wavelet parameters and earth model parameters are listed in Table 4.1. There are nine layers and eight boundaries, i.e., the top and bottom layers are treated as half-spaces. The boundary locations are the bottom of each layer in two-way travel time. The acoustic impedances in each layer are set at values appropriate for the thin coal seams
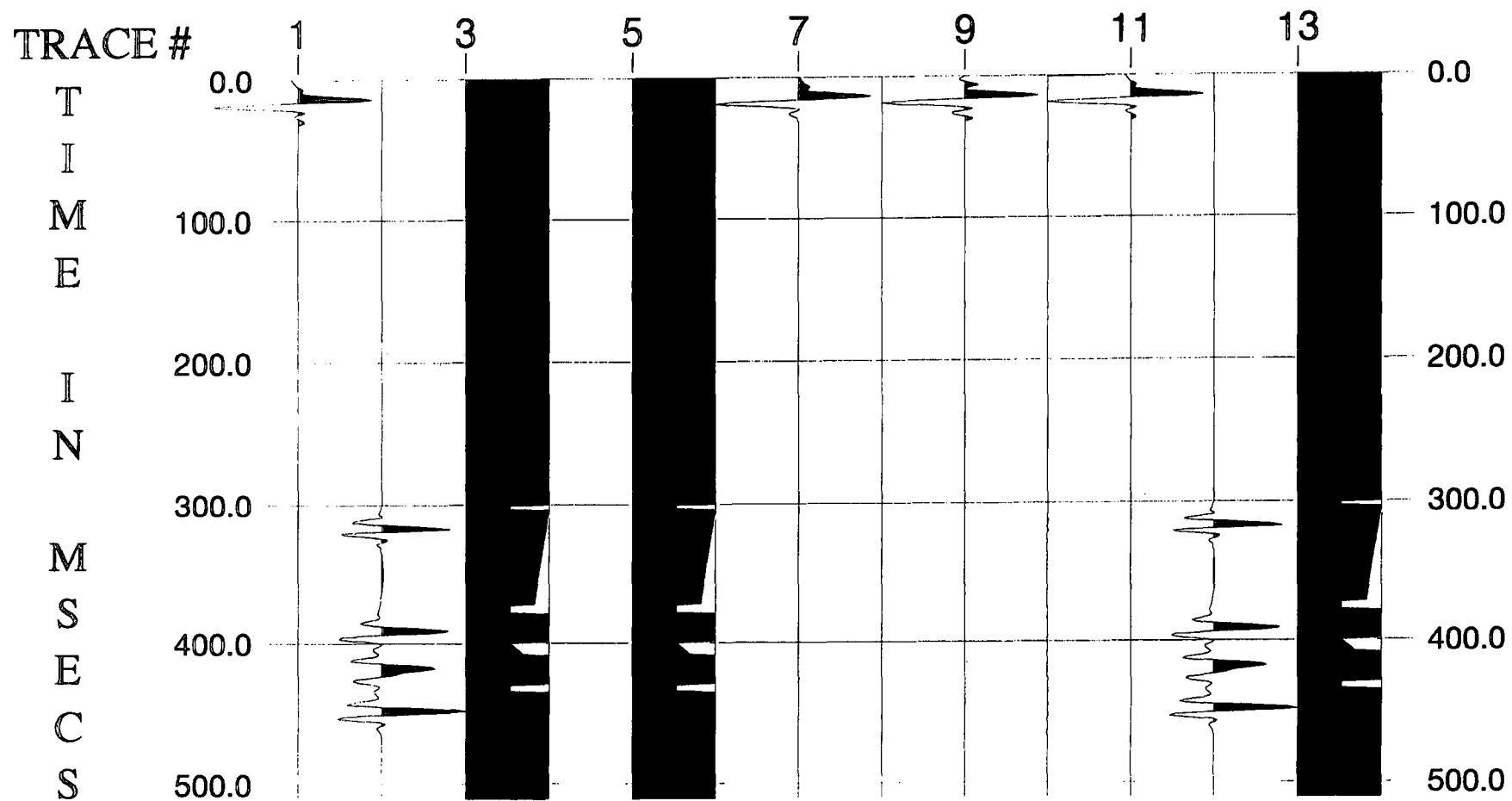
Figure 4.1 Synthetic inversion results for wavelet parameters and earth model with correct initial guess. Trace 1- synthetic wavelet; trace 2- synthetic trace; trace 3- synthetic earth model; trace 5-initial guess for the earth model; trace 7- extracted wavelet; trace 9- estimated 8-parameter wavelet; trace 10- error between synthetic and forward-modelled traces; trace 11- inverted wavelet; trace 12-forward-modelled trace; trace 13- inverted earth model.

and thick country rocks, at 4.0 and 7.6 $(g/cm^3)(km/s)$, respectively. The model is shown in Fig. 4.1 (trace 3).

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=20$ Hz		7.6	0.0
	301		
$f_2=30$ Hz		4.0	0.0
	304		
$f_3=90$ Hz		7.6	-0.02
	373		
$f_4=200$ Hz		4.0	0.0
	379		
$a_0=1.0$		7.6	0.0
	400		
$\varphi_0=90$ degree		4.0	0.15
	409		
$\varphi_1=0.1$ deg/Hz		7.6	0.0
	430		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.1 Synthetic wavelet and earth model

4.1.2 Wavelet Parameters

For the first test, the initial guess for the earth model is exactly the same as the real one. After a wavelet was extracted by a Wiener shaping filter, its phase spectrum was unwrapped and an 8-parameter wavelet was defined. Figure 4.1 shows the parameters of the synthetic example, the initial guess and the inversion results, ordered in the following way. Trace 1 is the synthetic wavelet used to generate the synthetic data (trace 2) with the reflection coefficient sequence resulting from the earth model shown on trace 3. Trace 5 shows the initial guess for the earth model. Traces 7 and 9 are the extracted wavelet and the estimate of the 8-parameter wavelet after phase unwrapping. After iterative inversion, trace 10 is the error between the synthetic and forward-

modelled trace. Traces 11 and 12 show the inverted wavelet and the forward-modelled trace. Trace 13 is the inversion result for the earth model.

For the extracted wavelet, the error energy between the synthetic trace and the forward-modelled trace is 0.11%. After phase unwrapping, the estimated values of the 8 parameters for the parameterized wavelet are shown in Table 4.2. For this estimate of the wavelet parameters, the error energy between the synthetic trace and the forward-modelled trace is 2.50 %.

$f_1 = 14$ Hz	$f_2 = 25$ Hz	$f_3 = 121$ Hz	$f_4 = 172$ Hz
$a_0 = 1.03$	$\varphi_0 = 89$	$\varphi_1 = 0.12$	$\varphi_2 = -0.002$
	degree	degree/Hz	degree/Hz^2

Table 4.2 The estimate for wavelet parameters
after phase unwrapping

The inversion result, following optimisation of the 8-parameter wavelet, shows that the inverted wavelet is even better than the extracted wavelet because the final error energy between the synthetic trace and forward-modelled trace after three iterations is equal to 0.01%. The parameters of the inverted wavelet are shown in Table 4.3.

$f_1 = 16$ Hz	$f_2 = 33$ Hz	$f_3 = 92$ Hz	$f_4 = 200$ Hz
$a_0 = 1.0$	$\varphi_0 = 90$	$\varphi_1 = 0.10$	$\varphi_2 = -0.002$
	degree	degree/Hz	degree/Hz^2

Table 4.3 Inverted wavelet after three iterations

This test is similar to the one we will carry out on the nearest trace to the well when inverting real data, where the initial guess for the earth model is almost correct based on the edited well log (see next chapter). In that case, before inverting for the wavelet

parameters, an initial inversion for the boundary locations is made using the extracted wavelet. However, for the synthetic test, this process is omitted.

If it is not possible to obtain an extracted wavelet, because no well log data are available, then it may be necessary to start with a guess wavelet, which could be in error. This case does not be apply for my real-data example. However, in order to show that problems exist in Cooke and Schneider's (1983) previous work, I give the following example. Consider the arbitrary initial guess for the wavelet parameters shown in Table 4.4. Its initial error energy is 42.63%. After inversion to optimise all the wavelet parameters, the error energy between the synthetic trace and the forward-modelled trace becomes 0.005%. The inverted wavelet parameters are listed in Table 4.5.

<center>8-parameter Guess Wavelet</center>

f_1=20 Hz	f_2=30 Hz	f_3=90 Hz	f_4=200 Hz
a_0 = 1.0	φ_0=45.0	φ_1 = 0.0	φ_2 = 0.0
	degree	degree/Hz	degree/Hz^2

<center>Table 4.4 Arbitrary initial guess for wavelet parameters</center>

<center>8-parameter Inverted Wavelet</center>

f_1=19 Hz	f_2=31 Hz	f_3=90 Hz	f_4=200 Hz
a_0 = 1.0	φ_0=90	φ_1 = 0.1	φ_2 = -0.002
	degree	degree/Hz	degree/Hz^2

<center>Table 4.5 Inverted wavelet for arbitrary initial guess</center>

From this result one can see that if the error in φ_0 between the guess wavelet (Table 4.4) and the synthetic wavelet (Table 4.1) is quite big, GLI still can find the correct answer for φ_0 as well as φ_1 and φ_2. One can also see that if the φ_0 values of the

actual wavelet and guess wavelet are different, the error energy without inversion is rather large and cannot be neglected. That is to say, this shows that Cooke and Schneider's (1983) conclusion (see §3.3.1) is not always correct. In the next section, this will also be shown together with inversion for the boundary locations.

4.1.3 Boundary Locations

Before any further inversion is discussed, it is necessary to see the inversion result for the boundary locations if there is no extracted wavelet available and just a guess wavelet has to be used. The result shows that if there are errors in the guess wavelet, the inversion will try to change the boundary locations to reduce the error energy even when the guess model of the boundary locations is correct. The guess wavelet is that given in Table 4.4. The initial error energy is still 42.63%, but the error energy after inverting for the boundary locations is 14.20% if there is no wavelet inversion. Table 4.6 shows the results of the inversion.

However, if the wavelet inversion is carried out before inverting for the boundary locations, the boundary locations remain unchanged and the error energy is also unchanged at 0.005%. Thus the wavelet plays just as important a role as the other earth model parameters in the inversion. This also shows the interference effects between the boundary locations and the wavelet parameters. Any errors in either guess model will affect the other, but provided one inverts for both wavelet and earth parameters, it may be possible to reach the global minimum.

For the following examples, the guess wavelet will be the same as the inverted wavelet in Table 4.3. Two iterations of the inversion procedure will be carried out in each case. Let us consider the case in which the guess model differs from the real model only in the boundary locations, as shown in Table 4.7.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
f_1=20 Hz		7.6	0.0
	300		
f_2=30 Hz		4.0	0.0
	303		
f_3=90 Hz		7.6	-0.02
	372		
f_4=200 Hz		4.0	0.0
	378		
a_0=1.0		7.6	0.0
	399		
φ_0=45 degree		4.0	0.15
	407		
φ_1=0.0 deg/Hz		7.6	0.0
	428		
φ_2=0 deg/Hz^2		4.0	0.0
	434		
		7.6	0.0

Table 4.6 Inverted boundary locations

for the guess wavelet of Table 4.4

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
f_1=16 Hz		7.6	0.0
	301		
f_2=33 Hz		4.0	0.0
	305		
f_3=92 Hz		7.6	-0.02
	370		
f_4=200 Hz		4.0	0.0
	380		
a_0=1.0		7.6	0.0
	401		
φ_0=90 degree		4.0	0.15
	409		
φ_1=0.1 deg/Hz		7.6	0.0
	432		
φ_2=-0.002 deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.7 Initial guess for the boundary locations

The initial error energy is 35.29%. Table 4.8 shows the final results after iterative inversion for boundary locations and wavelet parameters, yielding an error energy of 0.002%. The result is quite satisfactory and all the boundary locations are moved to the correct places.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=16$ Hz		7.6	0.0
	301		
$f_2=32$ Hz		4.0	0.0
	304		
$f_3=91$ Hz		7.6	-0.02
	373		
$f_4=200$ Hz		4.0	0.0
	379		
$a_0=0.99$		7.6	0.0
	400		
$\varphi_0=90$ degree		4.0	0.15
	409		
$\varphi_1=0.1$ deg/Hz		7.6	0.0
	430		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.8 Inverted boundary locations and wavelet parameters

It is important to estimate the reliability of this method when the differences between the guess and real earth model are increased, e.g. the guess model listed in Table 4.9. In this guess model, the errors in the boundary locations for the third coal seam (400 - 409 ms) are about 10 ms. I call this a "badly wrong" guess model for the boundary locations. In this case, the initial error energy was 82.26%. After inversion for boundary locations and wavelet parameters (Table 4.10), the final error energy was 6.5%.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=16\,Hz$		7.6	0.0
	301		
$f_2=33\,Hz$		4.0	0.0
	305		
$f_3=92\,Hz$		7.6	-0.02
	370		
$f_4=200\,Hz$		4.0	0.0
	380		
$a_0=1.0$		7.6	0.0
	410		
$\varphi_0=90$ degree		4.0	0.15
	419		
$\varphi_1=0.1$ deg/Hz		7.6	0.0
	432		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.9 Badly wrong initial guess for the boundary locations

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=20\,Hz$		7.6	0.0
	301		
$f_2=32\,Hz$		4.0	0.0
	304		
$f_3=85\,Hz$		7.6	-0.02
	373		
$f_4=205\,Hz$		4.0	0.0
	379		
$a_0=0.99$		7.6	0.0
	400		
$\varphi_0=111$ degree		4.0	0.15
	414		
$\varphi_1=-0.39$ deg/Hz		7.6	0.0
	430		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.10 Inverted boundary locations and wavelet parameters
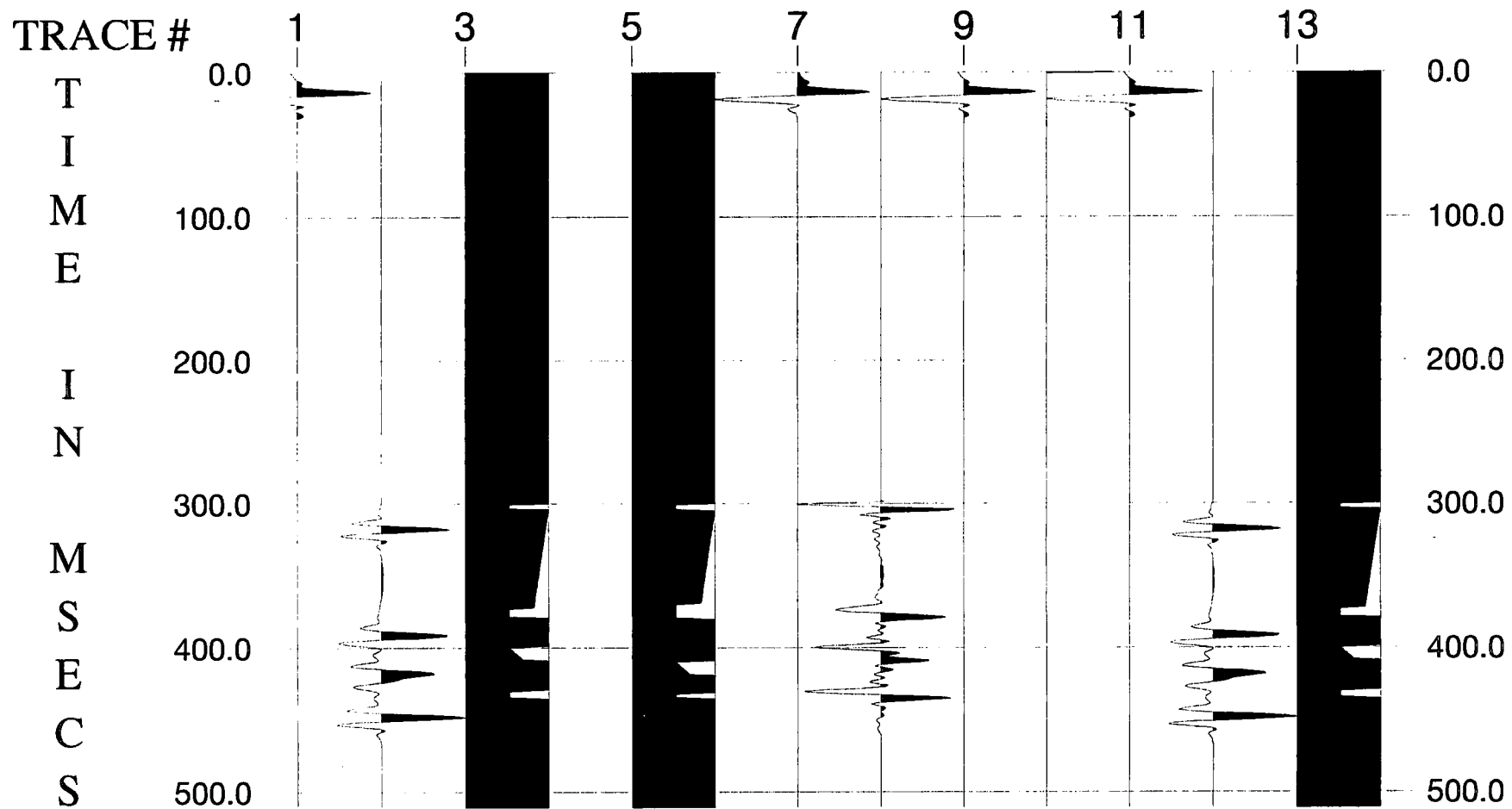
Figure 4.2 Synthetic inversion results for a badly wrong initial guess for the boundary locations with inversion for the reflection coefficient sequence applied prior to GLI with parameterization.

The inversion failed to get the correct answer for the bottom boundary locations of the third coal seam even though it improved on the initial guess. This indicates that the guess for boundary locations lies outside the "region of convergence" discussed by Cooke and Schneider (1983). This feature of the boundary locations indicates that the boundary locations are the most difficult of all parameters to invert. I will show later that a badly wrong initial guess for the acoustic impedance values can be correctly solved when the boundary locations are correct.

When dealing with real data, large differences between the initial guess and the real acoustic impedance distribution may result from faults, pinchouts, reefs or sand lenses. Normally those features are the exploration targets. Therefore I propose an alternative method for obtaining the initial guess of the acoustic impedance distribution. The first step is to invert for the reflection coefficient sequence directly from the seismic data using the best available wavelet estimate (see § 2.3). Applying this process to the synthetic trace using the inverted wavelet from Table 4.3 gives the spiked reflectivity shown as trace 8 on Fig. 4.2. This is equivalent to deconvolution using an optimum-lag Wiener spiking filter.

After estimating the reflection coefficient sequence (i.e., the spiked reflectivity), the program automatically searches for the eight most significant boundary locations. They are: 302, 305, 374, 380, 401, 410, 431, 436 ms, respectively. Then GLI with parameterization was applied, yielding the results shown in Fig. 4.2 and Table 4.11 with an error energy of 0.002 %. Comparing with the previous result, it is obvious that this method is successful. The advantage of this two-stage inversion procedure is that the boundary locations estimated from the spiked reflectivity, following deconvolution, should lie within the region of convergence for the subsequent application of GLI.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1 = 16\,Hz$		7.6	0.0
	301		
$f_2 = 32\,Hz$		4.0	0.0
	304		
$f_3 = 91\,Hz$		7.6	-0.02
	373		
$f_4 = 200\,Hz$		4.0	0.0
	379		
$a_0 = 1.0$		7.6	0.0
	400		
$\varphi_0 = 90$ degree		4.0	0.15
	409		
$\varphi_1 = 0.1$ deg/Hz		7.6	0.0
	430		
$\varphi_2 = -0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.11 Inverted boundary locations and wavelet parameters following

initial inversion for the reflection coefficient sequence

4.1.4 Acoustic Impedance and Gradients

In this section I will show that, if the initial guess for the boundary locations is correct and keep fixed, there will be no limitations on the acoustic impedance guess model because of the approximately linear relationship between the coefficients of the synthetic trace and the acoustic impedance values as expressed in equation (3.11). And even when there are some errors in the guess model for the boundary locations, it is still possible to get a nearly correct solution to the problem.

The guess earth model for the first example is listed in Table 4.12. There are some errors in the initial guess for acoustic impedance. The error energy after inversion for the boundary locations and the acoustic impedance values reduced from 9.20 % to 0.01 %. The final solution is shown in Table 4.13. This means if the guess for the

boundary locations is correct and the error energy for the initial guess is not big (up to, say, 30 %) , the correct boundary locations will remain unchanged in the inversion.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=16$ Hz		7.6	0.0
	301		
$f_2=33$ Hz		4.0	0.0
	304		
$f_3=92$ Hz		8.6	-0.02
	373		
$f_4=200$ Hz		4.0	0.0
	379		
$a_0=1.0$		6.0	0.0
	400		
$\varphi_0=90$ degree		4.0	0.15
	409		
$\varphi_1=0.1$ deg/Hz		5.6	0.0
	430		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.12 Initial guess for acoustic impedance values

In the next test, the initial guess for the acoustic impedance of the third layer was 3.6 instead of 8.6 $(g/cm^3)(km/s)$. For comparison this guess model can be considered as a "badly wrong" model for the acoustic impedance because the polarities are opposite to the true values for the acoustic impedance contrasts. The initial error energy was 61.36%. The results were almost the same as Table 4.13 with 0.05% error energy but without inversion for the boundary locations. This test shows that even though the acoustic impedance contrasts at the boundaries of the third layer have the wrong polarities, one can still get the correct answer as long as the initial guess for the boundary locations is correct and fixed. If the boundary locations are inverted as well as the acoustic impedance, they will affect each other. Table 4.14 shows the results and the error energy is 4.73%.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=16$ Hz		7.6	0.0
	301		
$f_2=31$ Hz		4.0	0.0
	304		
$f_3=91$ Hz		7.5	-0.02
	373		
$f_4=200$ Hz		4.0	0.0
	379		
$a_0=1.0$		7.5	0.0
	400		
$\varphi_0=90$ degree		4.0	0.15
	409		
$\varphi_1=0.1$ deg/Hz		7.5	0.0
	430		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.5	0.0

Table 4.13 Inverted boundary and acoustic impedance for Table 4.12

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=18$ Hz		7.6	0.0
	300		
$f_2=34$ Hz		4.0	0.0
	304		
$f_3=83$ Hz		7.1	-0.02
	373		
$f_4=200$ Hz		4.0	0.0
	378		
$a_0=1.0$		7.6	0.0
	399		
$\varphi_0=84$ degree		4.0	0.15
	409		
$\varphi_1=0.08$ deg/Hz		7.4	0.0
	430		
$\varphi_2=-0.003$ deg/Hz^2	435	4.0	0.0
		7.5	0.0

Table 4.14 Inverted boundary and acoustic impedance

for the badly wrong guess

In the next example, errors in the initial guess for the boundary locations, as in Table 4.7, as well as errors in the guess for the acoustic impedance and their gradients are included. This means that there are errors in all parameter types in the initial guess (Table 4.15). After iterative inversion for the boundary locations, the acoustic impedance and their gradients together, and the wavelet parameters, the error energy is reduced from 45.65% to 0.01% with the results shown in Table 4.16.

Overall, the inversion is fairly successful with no gross errors. However, it should be pointed out that the inverted acoustic impedance values and their gradient values contain some errors compared to the synthetic model, even though the total error energy is quite small. The first possible reason is that the model parameters interfere with each other and make the problem non-unique (or close to non-unique). The second reason for the errors in the acoustic impedance and gradients is the absence of low frequencies in the seismic data.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1 = 16$ Hz		7.6	0.0
	301		
$f_2 = 33$ Hz		4.0	0.0
	305		
$f_3 = 92$ Hz		8.6	0.0
	370		
$f_4 = 200$ Hz		4.0	0.0
	380		
$a_0 = 1.0$		6.0	0.0
	401		
$\varphi_0 = 90$ degree		4.0	0.0
	409		
$\varphi_1 = 0.1$ deg/Hz		5.6	0.0
	432		
$\varphi_2 = -0.002$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.15 Initial guess for all parameter types
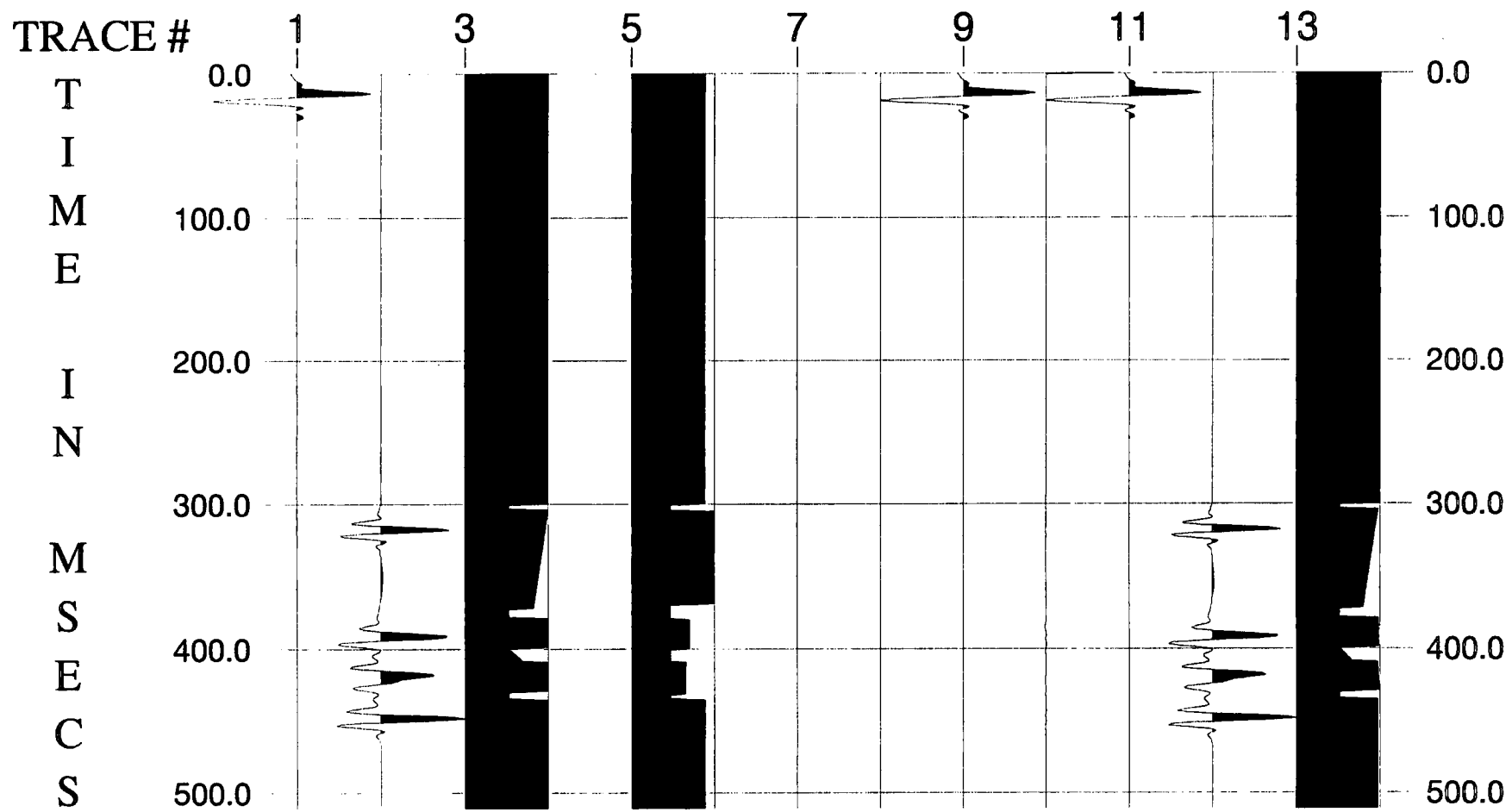
Figure 4.3 Synthetic inversion results for errors in the initial guess for all types of earth model and wavelet parameters.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1=16\,Hz$		7.6	0.0
	301		
$f_2=32\,Hz$		4.0	0.0
	304		
$f_3=90\,Hz$		7.5	-0.02
	373		
$f_4=199\,Hz$		4.0	-0.01
	379		
$a_0=1.0$		7.5	0.0
	400		
$\varphi_0=92$ degree		4.0	0.13
	409		
$\varphi_1=0.08$ deg/Hz		7.4	0.01
	430		
$\varphi_2=-0.002$ deg/Hz^2	435	4.0	0.0
		7.4	0.0

Table 4.16 Overall inversion results for initial guess in Table 4.14

Figure 4.3 shows the results of this inversion as a plot. The traces in this plot are ordered as in Fig. 4.1 (see § 4.1.2). A satisfactory feature is that the inverted boundary locations are correct even though there are some boundary location errors in the initial guess. Such errors are bound to exist in the initial guess models for inverting real data, so it is reassuring that the inversion methodology solves for them correctly in this noise-free synthetic data example. As for the errors in the acoustic impedance values and gradients, due to the missing low frequencies, they are not a big problem for inversion of Coal Measures data because the acoustic impedance can be fixed for coal seams. The changes in the thickness of the coal seams are the most interesting effect.

4.2 A 1-D Synthetic Model with White Noise

4.2.1 Introduction

There is always some noise present on observed seismic traces. Now let us consider the same model as in the previous section with 15% white noise (Gaussian distribution) added. In this section, the error energy will still be used to show the quality of the inversions and to measure the match between the synthetic data trace and the forward-modelled trace.

4.2.2 Wavelet Inversion

Following the processes described in §4.1.2, the inverted 8-parameter wavelet found after three iterations is listed in the following Table 4.17:

f_1=15 Hz	f_2=36 Hz	f_3=89 Hz	f_4=201 Hz
a_0 = 1.0	φ_0=89	φ_1 = 0.13	φ_2 = -0.002
	degree	degree/Hz	degree/Hz^2

Table 4.17 Inverted wavelet after three iterations

For the extracted wavelet, the error energy was 2.05%, but the initial guess for the 8-parameter wavelet gave an error energy of 4.71 %. After three iteration of inversion for the wavelet parameters, the error energy was only reduced to 2.17 %. Unlike the case without noise, the inverted 8-parameter wavelet is not as good as the extracted one. Therefore, it is necessary to look at the extracted wavelet and its spectra to decide whether it is suitable to use an 8-parameter wavelet in real data inversion. I will show in the next section that there are no big differences in the results between using the extracted
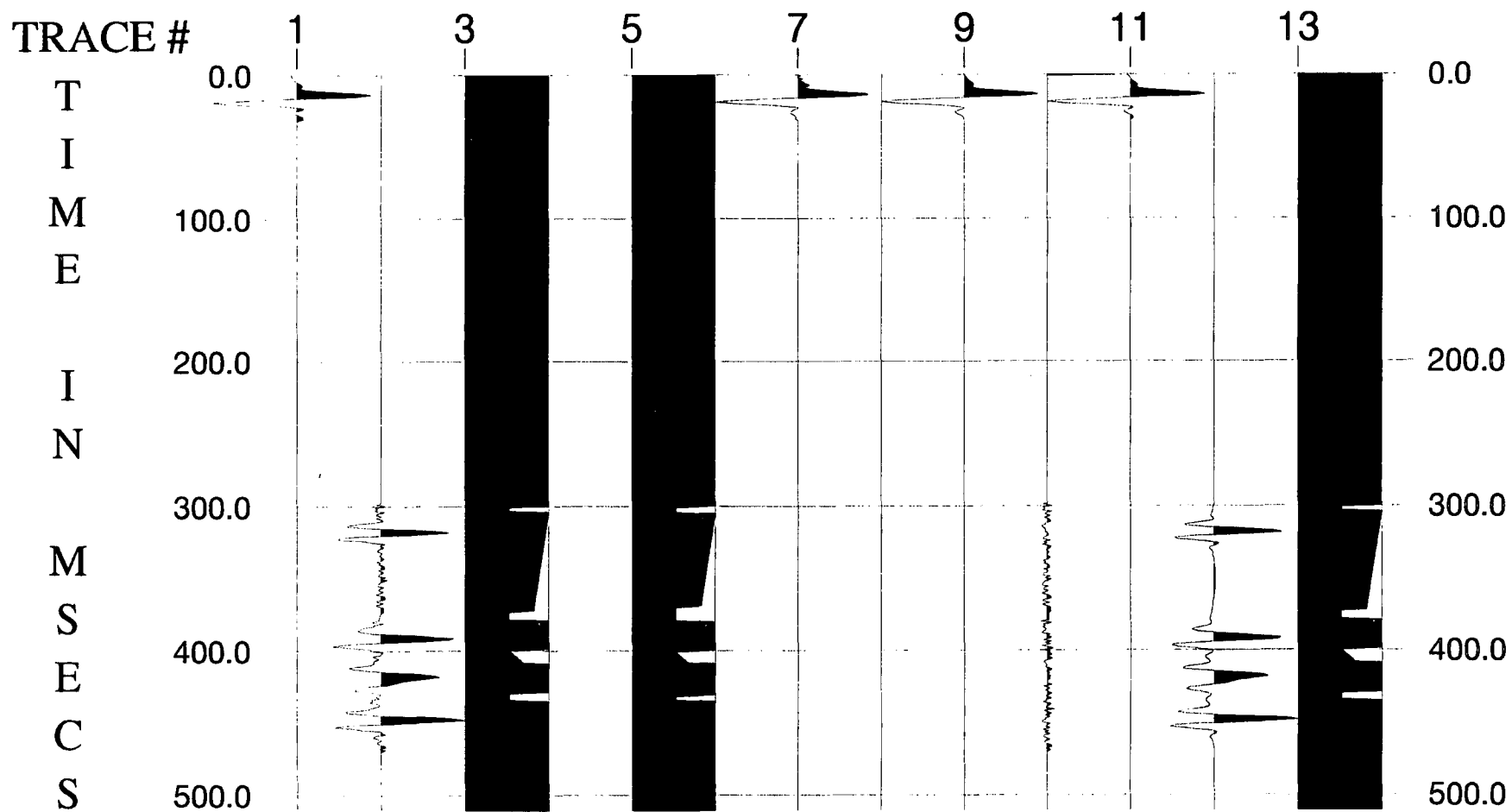
Figure 4.4 Synthetic inversion results with 15 % white noise on the input trace and errors in the initial guess for the boundary locations

wavelet and the 8-parameter wavelet in my synthetic examples, even though there are some differences in the error energy.

4.2.3 Boundary Locations

As in §4.1.3, the initial guess for the constant acoustic impedance values and gradients is the same as for the real forward model. The differences are in the boundary locations as given in Table 4.7. The results after inversion for boundary locations and the 8-parameter wavelet are shown in Table 4.18, with the error energy reduced from 31.59 % to 4.37 %. Figure 4.4 shows plots of the traces, in which the meaning of each trace is the same as described in §4.1.2.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1 = 16\,Hz$		7.6	0.0
	300		
$f_2 = 34\,Hz$		4.0	0.0
	304		
$f_3 = 86\,Hz$		7.6	-0.02
	373		
$f_4 = 204\,Hz$		4.0	0.0
	379		
$a_0 = 0.96$		7.6	0.0
	400		
$\varphi_0 = 89$ degree		4.0	0.15
	409		
$\varphi_1 = 0.12$ deg/Hz		7.6	0.0
	430		
$\varphi_2 = -0.003$ deg/Hz^2	435	4.0	0.0
		7.6	0.0

Table 4.18 Inverted boundary locations and wavelet parameters

Then I fixed the extracted wavelet in the inversion and compared the results. Though the error energy of 2.05% is a little bit better, the boundary locations were almost the

same, i.e. 301, 304, 373, 379, 400, 409, 430, 435 ms. Therefore, for the sake of being able to invert for wavelet parameters on successive traces, an 8-parameter wavelet defined in Table 4.17 is preferred and treated as the guess wavelet for the following inversions.

Comparing these results with §4.1.3, this inversion method shows its ability to invert the boundary locations when 15 % white noise is present on the observed trace, provided that the acoustic impedance values are correct.

4.2.4 Acoustic Impedance and Gradients

Using the same initial guess for the earth model as in Table 4.15 and the initial guess wavelet parameters as in Table 4.17, the final solution obtained by GLI with parameterization is listed in Table 4.19.

Wavelet	Bound. Locations (ms)	Acous. Impedance $(g/cm^3)(km/s)$	Ac. Imp. Gradient $(g/cm^3)(m/s^2)$
$f_1 = 13$ Hz		7.6	0.0
	301		
$f_2 = 38$ Hz		4.0	0.0
	305		
$f_3 = 88$ Hz		7.0	-0.01
	373		
$f_4 = 203$ Hz		4.0	-0.1
	379		
$a_0 = 1.0$		7.0	0.03
	400		
$\varphi_0 = 96$ degree		4.0	0.09
	409		
$\varphi_1 = -0.08$ deg/Hz		6.9	0.02
	430		
$\varphi_2 = -0.002$ deg/Hz^2	435	4.0	0.0
		7.2	0.0

Table 4.19 Inverted earth model and the wavelet parameters
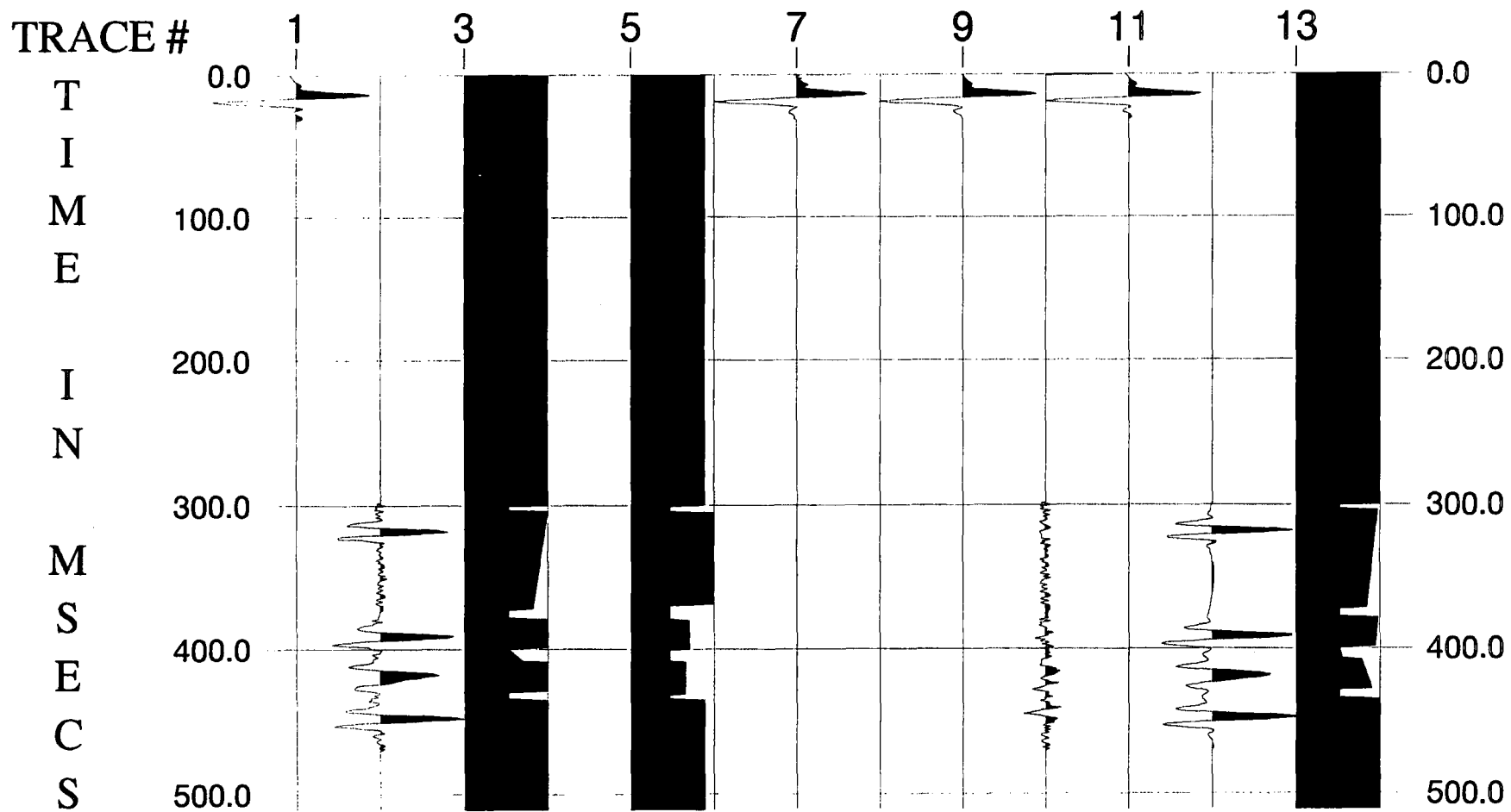
Figure 4.5 Synthetic inversion results with 15 % white noise on the input trace and errors in the initial guess for all types of earth model and wavelet parameters.

For this inversion, the error energy is reduced from 41.78% to 3.52 %. The results are also shown in Fig. 4.5. Comparing Table 4.19 with Table 4.16, one can see the inversion almost succeeded in locating the boundaries, with only a small error in the boundary at 304 ms, even though 15 % white noise had been added. That is to say, when white noise is present on the observed trace, if boundary locations and acoustic impedances are all in error in the guess model, GLI with parameterization can still find the correct answer for the boundary locations. However, the inverted values of the acoustic impedance and its gradient are worse than the result in the noise-free case. This indicates that acoustic impedance values are more sensitive to white noise on the observed trace than the boundary locations and wavelet parameters are, at least when the SNR is not too poor.

4.3 Summary

A number of synthetic examples either with noise-free or with some white noise have been presented. It can be seen that it is possible to use this GLI method to do some inversion on post-stack seismic data in the thin bed area as long as the boundary locations are carefully treated and the noise on the observed traces is not severe. Furthermore, for the badly wrong initial guess for the boundary locations, it is still possible to get the correct answer by applying an inversion for the reflection coefficient sequence and then GLI. For the badly wrong initial guess for the acoustic impedance values, it can obtain the correct solutions only if the initial guess for the boundary locations is correct and fixed.

In this chapter, I have reported results from several different tests on synthetic data. I give a summary table below (Table 4.20) which shows where incorrect parameters were assigned in the initial guess, the inversion procedure applied and the error energy in the result. Corresponding table numbers are given for each test, as available.

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Without Noise	Initial Guess Model		Inversion Procedure	Error Energy
	Earth	Wavelet		
Table 4.3	Correct	None	Wavelet extraction and wavelet parameters	0.01 %
Table 4.5	Correct	Wrong	Wavelet parameters only	0.005 %
Table 4.6	Correct	Wrong	Boundary locations only	14.20 %
	Correct	Wrong	Boundary locations and wavelet parameters	0.005 %
Table 4.8	Bdary. locns. wrong	Inverted	Boundary locations and wavelet parameters	0.002 %
Table 4.10	Bdary. locns. badly wrong	Inverted	Boundary locations and wavelet parameters	6.5 %
Table 4.11	Bdary. locns. badly wrong	Inverted	Reflection coefficient sequenc, then as above	0.002 %
Table 4.13	Acoustic imp. wrong	Inverted	Boundary locations and acoustic impedance inversion	0.01 %
	Acoustic imp. badly wrong	Inverted	Acoustic impedance inversion	0.05 %
Table 4.14	Acoustic imp. badly wrong	Inverted	Boundary locations and acoustic impedance inversion	4.73 %
Table 4.16	Everything wrong	Inverted	Bdary. locns., acoustic imp. and wavelet parameters	0.01 %
With 15 % White Noise				
Table 4.17	Correct	None	Wavelet extraction and wavelet parameters	2.05 %
Table 4.18	Bdary. locns. wrong	Inverted	Boundary locations and wavelet parameters	4.37 %
	Bdary. locns. wrong	Extracted	Boundary locations inversion only	2.05 %
Table 4.19	Everything wrong	Inverted	Bdary. locns., acoustic imp. and wavelet parameters	3.52 %

Table 4.20 Brief summary of inversion tests and results

for a synthetic data example

5 British Coal's Dataset

5.1 Introduction

In this chapter, I present the results of applying inversion to the reprocessed migrated dataset from British Coal. Due to the complexity of the stratigraphy, it was necessary to start the inversion at a borehole and to do some systematic work to determine the most important model parameters at that borehole. According to the well logs, two different inversion windows were chosen for Thorny Plantation and Pillbox boreholes in order to cover all the coal seams present.

For the real data, the scaling factor between the forward-modelled trace and the observed trace is unknown. Furthermore, for inverting the seismic section, it is necessary to normalise the total energy of the signal in the inversion window on each trace to the same value. Therefore, the acoustic impedance in the coal seams was fixed to provide a consistent scaling for all the acoustic impedance values. Then I calculated the total energy in the chosen window on the observed trace at the borehole and took this value to normalize the total energy in the chosen window for each trace in the section.

In addition, even though I carefully reprocessed the seismic reflection data, the amplitude values of the reflection events on the seismic trace are still not the true relative amplitude values, which are important for thin bed inversion. In the synthetic examples, there are no such problems. I will point out the effect of incorrect relative amplitude values on the inversion for the thicknesses of the coal seams in the following systematic study.

5.2 Systematic Study at Thorny Plantation

5.2.1 Comparison of the Two Different Processed Sections

In this section, I will first quantify the improvement achieved with the reprocessed data, compared to the section obtained by the British Coal's original processing, by making use of the well logs. The criterion for the comparison is the error energy between the observed data and the forward-modelled trace obtained by convolving the extracted wavelet with the reflection coefficient sequence generated from the well logs.

This procedure was applied for the trace at CDP 994 from British Coal's processing and from my processing. The window on the observed trace was taken to be 331 ms to 480 ms in each case to cover all the coal seams. For each processed trace at CDP 994, the normal equations for a Wiener shaping filter were solved to extract a wavelet as the best filter, in a least squares sense, for shaping the reflection coefficient sequence obtained from the well logs into the processed trace. The length of the wavelet was chosen to be 32 ms. Then the error energy was calculated between the forward-modelled trace and the observed (i.e. processed) trace. Finally, these two values of error energy were compared to see which was smaller. The results were 29.74% for British Coal's data and 24.64% for my reprocessed data.

The optimum time shifts for the two observed traces are slightly different: the observed trace was lagged relative to the reflection coefficient sequence by 9 ms for British Coal's data and 11 ms for my reprocessed data.

The results imply that the reprocessed data are an improvement on British Coal's. From now on, only the reprocessed dataset will be considered for analysis and discussion.

Figure 5.1 Relationship between the time shift and error energy for all 31 positions of the desired output when extracting the wavelet at Thorny Plantation borehole.
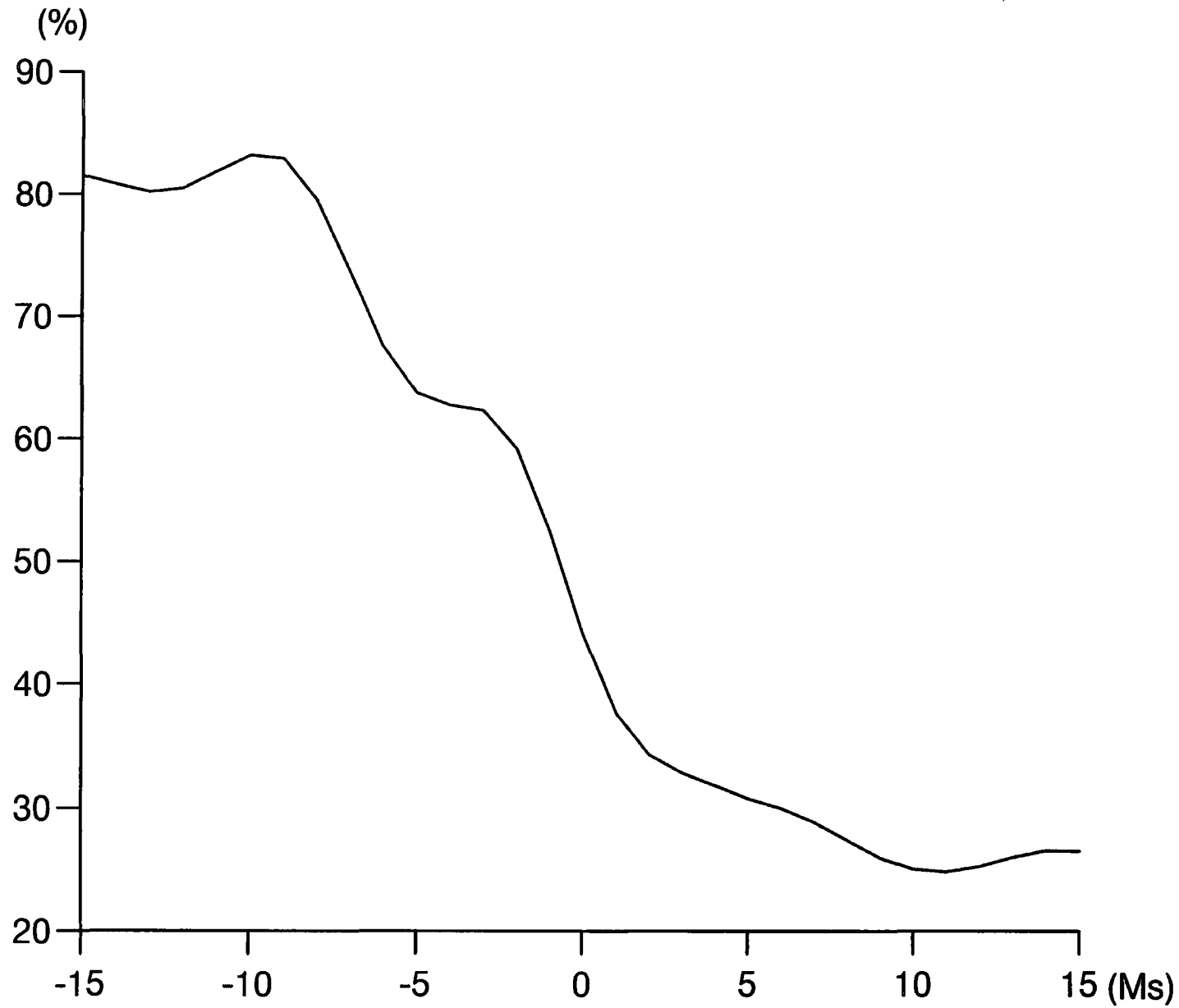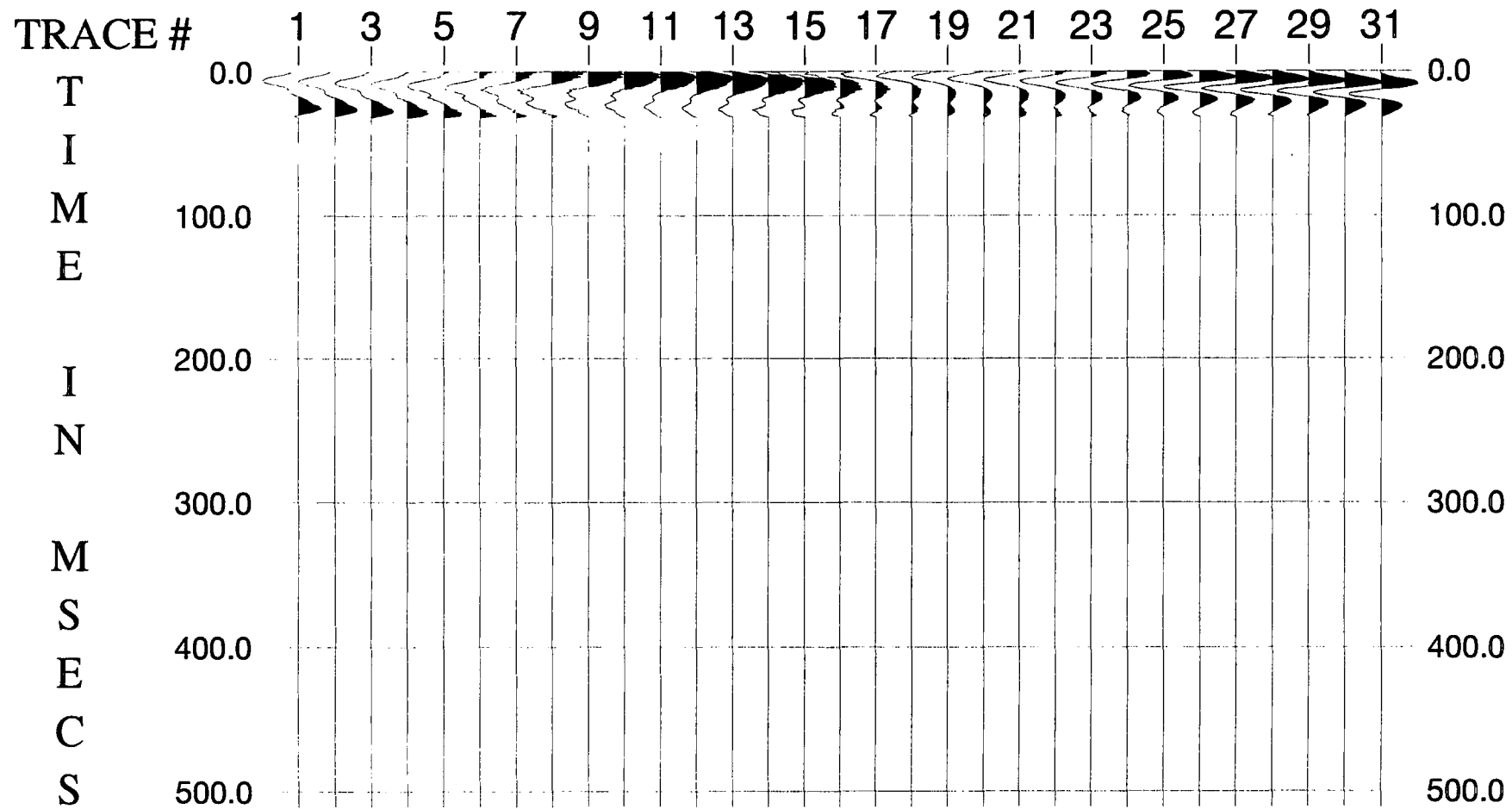
Figure 5.2 All the extracted 31 wavelets at Thorny Plantation borehole.

5.2.2 Time Shift for the Extracted Wavelet

In the previous section, it was noted that there is a time shift associated with the optimum extracted wavelet. After comparison of the observed trace with the well log at Thorny Plantation borehole, the length of the maximum time shift was set to be 15 ms · during this procedure. Figure 5.1 shows the relationship between the time shift and error energy for all 31 positions of the desired output (the observed trace window) relative to the input (the reflection coefficient sequence). The minimum error energy corresponds to a time lag of the desired output by 11 ms.

The extracted wavelets do not only differ by a time shift but also have different shapes. Figure 5.2 shows all the 31 wavelets extracted in this process, trace 1 corresponding to a time shift of -15 ms, trace 2 to -14 ms, and so forth. Note that trace 27 is the optimum extracted wavelet in this example. In order to compare the inversion result with the processed section, the reflection coefficient sequence was moved back 11 ms to match the observed trace.

5.2.3 Identification of the Main Coal Seams

It may be seen from the well logs (Figure 3.20) that several coal seams could be responsible for events on the seismic section. In order to use the minimum number of earth model parameters, it was necessary to determine which are the dominant coal seams that generated the main reflections on the observed trace, and just invert to optimize their parameters. In this procedure, the time window between 331 ms and 480 ms was again chosen to cover all the coal seams.

The method I used was simply to carry out a sequence of trials. Firstly, the most dominant coal seam was determined by making a one-layer guess model for each coal

Figure 5.3 Contributions of the various coal seams to reduction of the error energy following inversion at CDP 940, the nearest CDP to Thorny Plantation borehole.
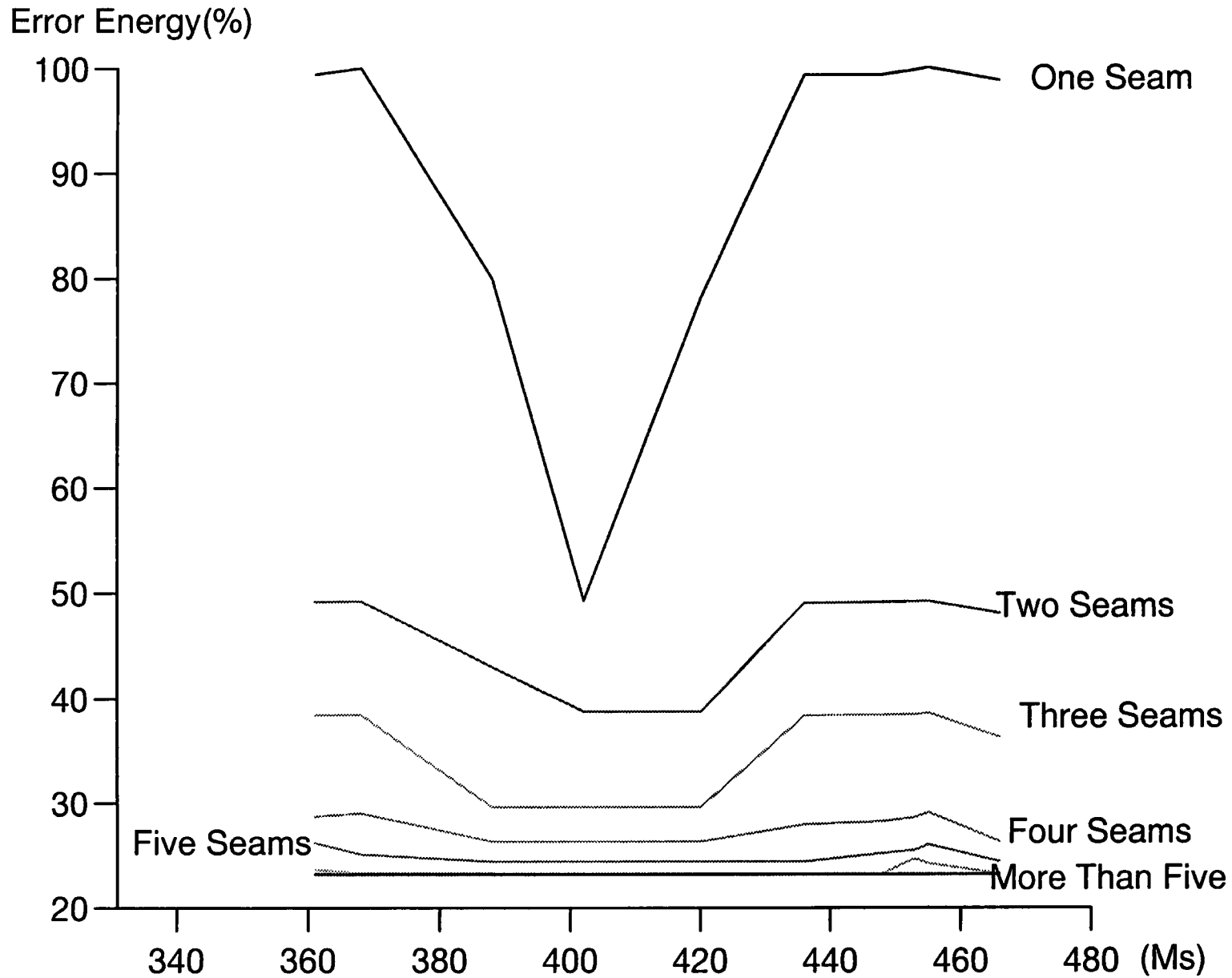
seam in turn. According to the well logs and lithology information at Thorny Plantation (Figs. 3.17 and 3.20), there are 10 coal seams in this borehole, and the acoustic impedances of coal seams and country rocks are approximately 4.0 and 7.6 $(g/cm^3)(km/s)$, respectively. For each coal seam, a boundary location inversion by GLI was applied. The correlation coefficient and error energy between the synthetic trace calculated from this inverted model and the observed trace is given in Table 5.1. The most dominant coal seam is obviously the one at 402-409 ms as it has the largest correlation coefficient and the least error energy.

Guess Coal Seams (ms)	Corr. Coefficient	Error Energy	Inverted Boundary
359 - 362	0.0765	99.42 %	361 - 362 (ms)
367 - 369	0.0	100.0 %	368 - 368 (ms)
386 - 391	0.4531	79.91 %	387 - 390 (ms)
401 - 406	0.7883	49.25 %	402 - 409 (ms)
422 - 427	0.4675	78.14 %	420 - 429 (ms)
435 - 438	0.0830	99.33 %	436 - 438 (ms)
447 - 450	0.0816	99.34 %	448 - 449 (ms)
453 - 454	0.0570	99.74 %	453 - 454 (ms)
457 - 459	0.0	100.0 %	455 - 455 (ms)
463 - 466	0.1273	98.79%	466 - 468 (ms)

Table 5.1 Searching for the most dominant coal seam at Thorny Plantation

The second trial was to take this dominant coal seam with each of the other nine coal seams in turn, and use GLI to optimize the boundary locations to find which pairing is the most dominant. Repeating this procedure for combinations of three seams, four seams, and so on, determines the contributions of all coal seams in order. Figure 5.3 shows the relative size of their contributions.

The ordering of the coal seams turned out to be the same as in the first trial for individual seams. However, only after all the trials had been done could the error energy and correlation coefficient for each optimum combination be found. From Fig. 5.3, it can be

seen that for more than three trials, the decrease in error becomes very small. I should point out that with five or more coal seams, the correlation coefficient and error energy (0.8841 and 24.42 %) are even better than those obtained from the well logs (0.8729 and 24.64%). This is because there were some errors in the well logging and some noise on the observed seismic trace. Consequently, as more and more earth model parameters are introduced for inversion, the fit will progressively improve, and at some point will become better than the fit from any fixed earth model.

The optimum combination of three main coal seams accounts for more than 80% of the energy on the observed trace at Thorny Plantation borehole. Therefore, these three coal seams were taken as the target seams to invert, together with the immediately underlying seam, which was included to ensure to optimum inversion for the middle two thickest coal seams.

5.2.4 Construction of Initial Guess for the Earth Model

Based on the previous discussion, the four chosen coal seams are at two-way times given by the well log information (Fig. 3.20) as follows: Black Rake at 389 - 391 ms, Deep Main at 402 - 407 ms, Parkgate/Tupton at 422 - 428 ms and Yard at 436 - 437 ms. In order to get a better estimate of the extracted wavelet, a shorter time window between 380 ms and 439 ms was chosen and the optimum wavelet was again found by solving the normal equations for a Wiener shaping filter. The corresponding time shift was a lag of the desired output by 10 ms. The wavelet used for constructing the guess earth model was the extracted wavelet.

The acoustic impedance values of the top and bottom coal seams were set to be 4.0 $(g/cm^3)(km/s)$ and of the two middle main coal seams were set to be 3.0 $(g/cm^3)(km/s)$, all with gradients of zero. These values were fixed for all inversions run along the seismic sections. The acoustic impedance values and gradients are more difficult to cope with for

the country rocks because they are average contributions from different lithologies. When the acoustic impedance values were treated as variable parameters, they were constrained between values of 12.0 and 5.0 $(g/cm^3)(km/s)$, chosen according to the maximum range of values on the well logs.

Because the initial guess earth model was to be constructed at the borehole, it seemed reasonable to assume that the boundary locations of these coal seams and the wavelet are almost correct. Based on this, I fixed all the parameters apart from the acoustic impedance values of the country rocks, and inverted for them. However, the results gave acoustic impedance values which were not at all similar to their values known from well log information. As a cross-check, I fixed the acoustic impedance values from the well logs and inverted for the boundary locations. The results were also unsatisfactory because the Deep Main seam was apparently thicker than Parkgate/Tupton. This is not true according to the well log information. It is not possible for the seam thicknesses and the acoustic impedance values given by the well logs to be so badly wrong. The discrepancy must result from problems with the observed trace, which is only crudely approximated by the simple convolutional model.

In order to make progress with inverting the seismic section, a decision had to be taken on which parameters were the interesting ones to invert, the thicknesses of the coal seams or the acoustic impedance values. Either an increase in the thicknesses of the coal seam or an increase in the acoustic impedance contrast will cause the amplitude of the seismic trace to increase (Widess, 1973). Therefore, I chose to fix the boundary locations and acoustic impedance values of the coal seams from the well logs, and to invert for the acoustic impedance values of the country rocks to get the best fit to the observed trace at the borehole. The results comprise the initial guess for the earth model, shown in Table 5.2. The acoustic impedance values of the country rocks obtained are not true values, but simply the best-fitting values for the known parameters of the coal seams.

Boundary Locations (ms)	Acoustic Impedance (g/cm^3)(km/s)	Acous. Imp. Gradients (g/cm^3)(m/s^2)
	6.9	0.0
389		
	4.0	0.0
391		
	9.9	0.0
402		
	3.0	0.0
407		
	6.0	0.0
422		
	3.0	0.0
428		
	5.5	0.0
436		
	4.0	0.0
437		
	7.6	0.0

Table 5.2 Initial guess earth model at Thorny Plantation borehole

If we assume that the forward-modelled trace generated by convolving the extracted wavelet with the reflection coefficient sequence from the well logs is a signal trace, the difference between the observed trace and this synthetic trace should be the noise trace. The signal-to-noise amplitude ratio is calculated as 1:0.1592 (or greater than 6:1), which is similar to our synthetic example with 15 % random noise added.

The correlation coefficient and error energy are 0.9518 and 9.12 % for this earth model with the extracted wavelet. It is interesting to note that the error energy is less than that obtained (10.29 %) using the complete reflection coefficient sequence from the well logs with the same extracted wavelet. This suggests that our initial guess earth model is quite good and also that there are some errors on the well logs.

Figure 5.4 Amplitude and phase spectra of the extracted wavelet at CDP 940, close to Thorny Plantation borehole.
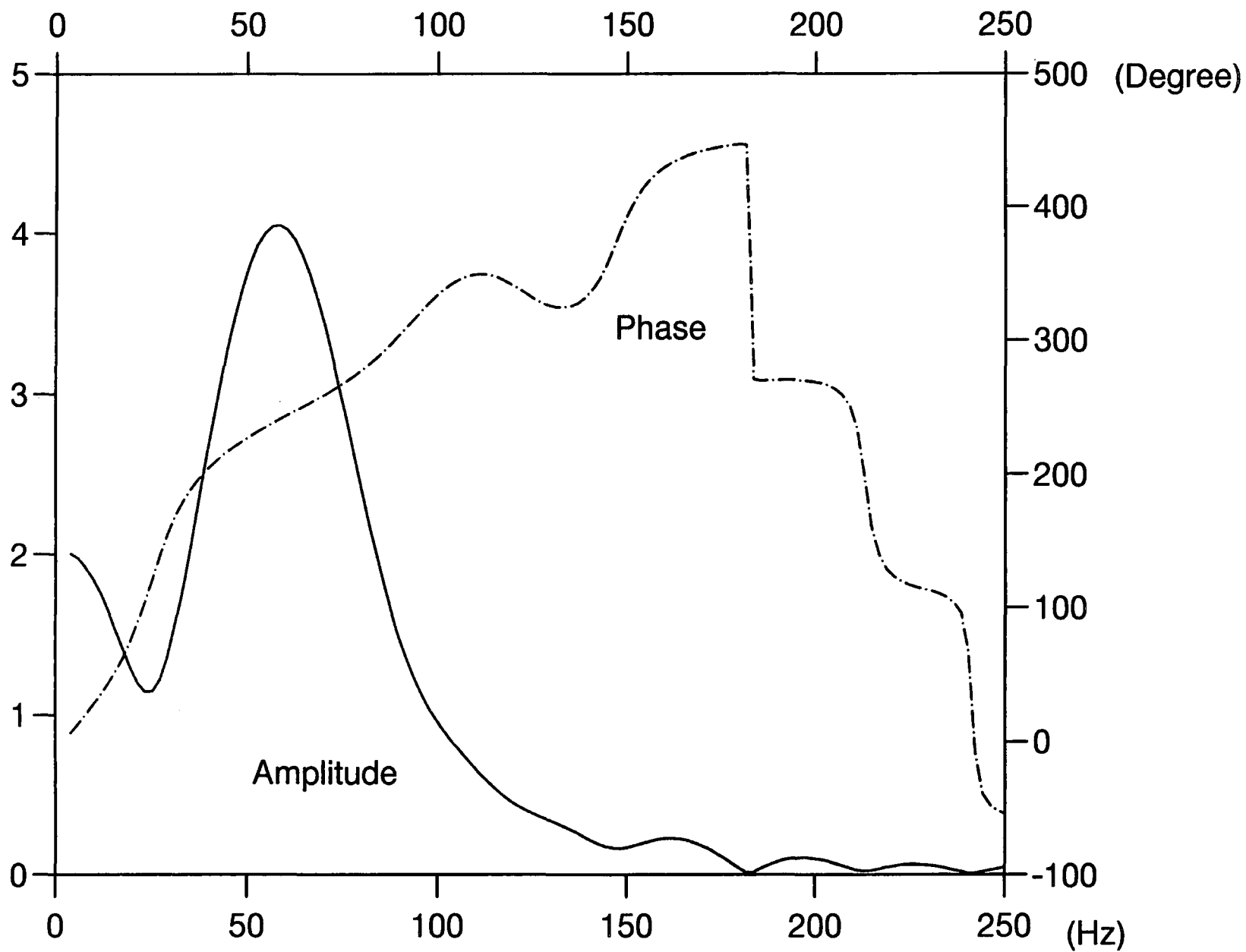
5.2.5 Estimation of Wavelet Parameters

The amplitude spectrum and phase spectrum of the optimum extracted wavelet are plotted in Fig. 5.4. From this diagram, it can be seen that the boxcar-with-cosine-tapers, defined by four frequencies, is a reasonable approximation to represent the amplitude spectrum of the extracted wavelet. After fitting the eight parameters to these spectra (Table 5.3) to parameterize the wavelet in the frequency domain, the error energy between the forward-modelled and observed traces was 13.78%.

The next step was to perform GLI for the wavelet parameters for three iterations whilst keeping the earth model fixed, as shown in Table 5.2. The error energy between the forward-modelled and observed traces was reduced to 5.92%, which is less than that found when using the extracted wavelet (9.12%). These optimized values (Table 5.4) comprise the initial guess for the wavelet parameters, and can be seen in Fig. 5.4 to provide a reasonably accurate representation of the extracted wavelet.

$f_1 = 14$ Hz	$f_2 = 39$ Hz	$f_3 = 76$ Hz	$f_4 = 136$ Hz
$a_0 = 6.45$	$\varphi_0 = 26$	$\varphi_1 = 5.23$	$\varphi_2 = -0.02$
	degree	degree/Hz	degree/Hz^2

Table 5.3 Estimated wavelet parameters after fitting the spectra

$f_1 = 18$ Hz	$f_2 = 42$ Hz	$f_3 = 57$ Hz	$f_4 = 150$ Hz
$a_0 = 6.17$	$\varphi_0 = 80$	$\varphi_1 = 3.67$	$\varphi_2 = -0.01$
	degree	degree/Hz	degree/Hz^2

Table 5.4 Initial guess for the wavelet parameters

after optimizing the fitted values

5.2.6 Inversion of the Trace at the Borehole

In the preceding five sub-sections, I have described how the initial guess model was established for the boundary locations, acoustic impedance values and gradients, and the wavelet parameters. The earth model parameters for the initial guess are given in Table 5.2 and the wavelet parameters in Table 5.4. The next steps were to apply GLI separately for the boundary locations, acoustic impedance parameters for the country rocks and wavelet parameters. This was done consecutively over two complete iterations of the three-stage inversion process.

Because of the relatively accurate information from the initial guess for the boundary locations, there were only small changes in the boundary locations and wavelet parameters, but some big changes in the acoustic impedance parameters. Final values are shown in Table 5.5 and yield an error energy of 2.15 %.

Wavelet	Bound. Locations. (ms)	Acous. Impedance. $(g/cm^3)(km/s)$	Ac. Imp. Gradients $(g/cm^3)(m/s^2)$
$f_1 = 13$ Hz		9.1	0.0
	390		
$f_2 = 42$ Hz		4.0	0.0
	391		
$f_3 = 53$ Hz		12.0	0.0
	402		
$f_4 = 151$ Hz		3.0	0.0
	407		
$a_0 = 6.17$		7.1	0.0
	421		
$\varphi_0 = 79$ degree		3.0	0.0
	427		
$\varphi_1 = 3.67$deg./Hz		5.0	0.0
	436		
$\varphi_2 = -0.01$		4.0	0.0
	437		
$(degree/Hz^2)$		5.0	0.0

Table 5.5 Inversion results at Thorny Plantation borehole
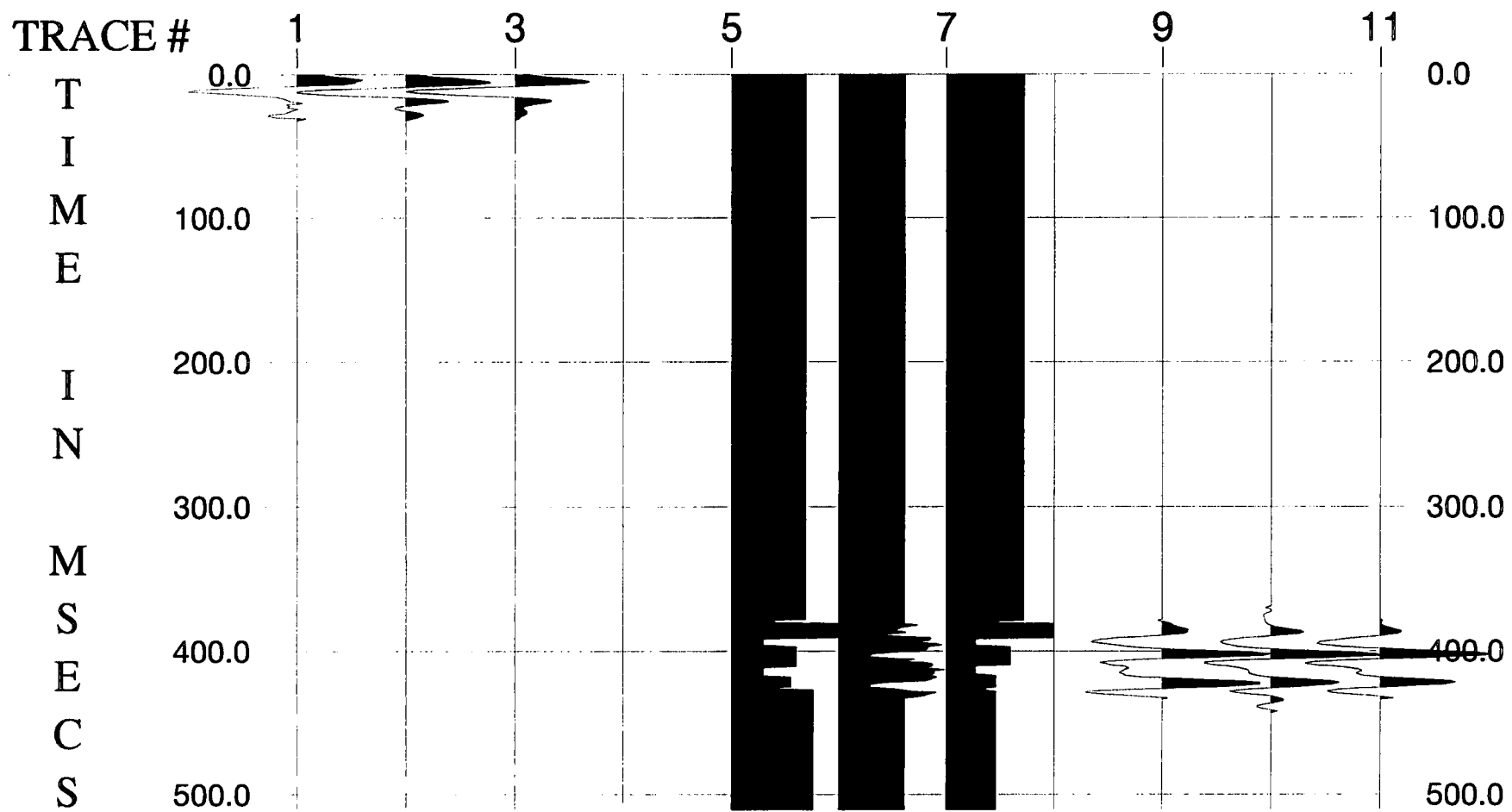
Figure 5.5a Inversion results for all parameters at CDP 940.

The stability of the boundary locations with respect to their locations in the well logs is satisfactory. Also, the 8-parameter wavelet seems to represent the extracted wavelet satisfactorily in Thorny Plantation. However, noise on the observed trace is presumably responsible for the discrepancy between the inverted acoustic impedance parameters and those found from the well logs.

Figure 5.5a shows the results of this procedure for the trace at CDP 994. Trace (1) is the extracted wavelet. Trace (2) is the estimated wavelet after phase unwrapping. Trace (3) is the inverted wavelet. Trace (5) is the initial guess for the earth model. Trace (6) is the well log at Thorny Plantation. Trace (7) is the inverted earth model. Trace (9) is the forward-modelled trace calculated from the extracted wavelet and well log data. Trace (10) is the observed trace at CDP 994. Trace (11) is the forward-modelled trace from the inverted wavelet and inverted earth model at CDP 994.

5.3 Systematic Study At Pillbox

Similar to the work at Thorny Plantation borehole,I carried out a systematic study at Pillbox borehole using the nearest trace at CDP 1230.

The optimum time shift calculated during wavelet extraction was a time lag of the desired output by 38 ms compared to 11 ms at Thorny Plantation borehole. This means that there has been some change in the datum level, either on the seismic section or between the well logs. I think it is due to the well logs because I reprocessed the seismic data along the section, paying particular attention to the field statics and autostatics, and judge that it is impossible to cause such a big datum difference. In this respect, my processing was also consistent with British Coal's. It is easy to see that the optimum time shift calculated at Pillbox borehole is about right by locating the Deep Main horizon on the reprocessed

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section at the right hand side (350 ms - see Fig. 3.14) and comparing it with the well logs (386 ms - see Fig. 3.21).

Then I attempted to identify the most dominant coal seams among the ten seams present in Pillbox borehole (Fig. 3.21). The search window was between 310 and 460 ms to include all the ten coal seams. The acoustic impedance values were set to be 4.0 $(g/cm^3)(km/s)$ for coal seams and 7.6 $(g/cm^3)(km/s)$ for country rocks, as at Thorny Plantation borehole. Fortunately, the results were similar to those obtained at Thorny Plantation (Table 5.6). The three dominant coal seams are the Black Rake (370 - 375 ms), Deep Main (383 - 390 ms) and Parkgate/Tupton (399 - 406 ms). Again I chose these coal seams as the target seams to invert, together with the immediately underlying Yard seam (413 - 417 ms) to ensure optimum inversion for the middle two thickest coal seams.

Guess Coal Seams (ms)	Corr. Coefficient	Error Energy	Inverted Boundary
347 - 348	0.3308	89.11 %	347 - 352 (ms)
355 - 357	0.1624	104.2 %	355 - 356 (ms)
368 - 374	0.3997	84.08 %	370 - 375 (ms)
384 - 390	0.5182	75.14 %	383 - 390 (ms)
401 - 406	0.4501	80.21 %	399 - 406 (ms)
414 - 416	0.2764	92.50 %	413 - 417 (ms)
426 - 428	0.1472	97.90 %	426 - 428 (ms)
430 - 431	0.0739	99.48 %	430 - 431 (ms)
436 - 437	0.0	100.0 %	436 - 436 (ms)
442 - 443	0.0565	99.76%	441 - 442 (ms)

Table 5.6 Searching for the most dominant coal seams at Pillbox

In order to get a better estimate of the extracted wavelet, a new shorter inversion window was set from 331 to 395 ms, which takes into account the 38 ms time shift and keeps almost the same length as at Thorny Plantation for comparison. The error energy between the observed trace and the forward-modelled trace obtained from the well logs was 24.52 %. That is to say, the SNR (1:0.3716, or less than 3:1) of the observed trace at

Pillbox is worse than the SNR (1:0.1592) at Thorny Plantation. Also it can be seen on Fig. 5.5b that the extracted wavelet is very complicated.

The next step was to obtain an initial guess earth model for subsequent optimization of wavelet and earth model parameters. As described in §5.2.4, a decision should be made before constructing the initial guess for the earth model. Therefore I decided to use the boundary locations obtained from Pillbox borehole. Then I inverted for the acoustic impedance values to obtain the initial guess for the earth model, as shown in Table 5.7. Due to the relatively small reflection from the Parkgate/Tupton seam at this trace, the acoustic impedance values of the country rock above and below this seam became very small, which does not match the well log information.

Boundary Locations (ms)	Acoustic Impedance $(g/cm^3)(km/s)$	Acous. Imp. Gradients $(g/cm^3)(m/s^2)$
	5.5	0.0
372		
	4.0	0.0
374		
	7.7	0.0
384		
	3.0	0.0
389		
	5.0	0.0
401		
	3.0	0.0
407		
	5.3	0.0
414		
	4.0	0.0
415		
	6.7	0.0

Table 5.7 Initial guess earth model at Pillbox borehole

The eight parameters of the wavelet after phase unwrapping and fitting the spectra are shown in Table 5.8. The parameters were then optimized by three iterations of GLI whilst

keeping the earth model fixed (Table 5.7) to give the initial guess for the wavelet

parameters in Table 5.9.

$f_1 = 42$ Hz	$f_2 = 55$ Hz	$f_3 = 78$ Hz	$f_4 = 138$ Hz
$a_0 = 3.62$	$\varphi_0 = -22$	$\varphi_1 = -1.16$	$\varphi_2 = 0.01$
	degree	degree/Hz	degree/Hz^2

Table 5.8 Estimate of the wavelet parameters

after fitting the spectra

$f_1 = 41$ Hz	$f_2 = 55$ Hz	$f_3 = 76$ Hz	$f_4 = 138$ Hz
$a_0 = 2.80$	$\varphi_0 = -24$	$\varphi_1 = -1.64$	$\varphi_2 = 0.03$
	degree	degree/Hz	degree/Hz^2

Table 5.9 Initial guess for the wavelet parameters

after optimizing the fitted values

The error energy and the correlation coefficient are equal to 25.48 % and 0.8876 for the

initial guess wavelet in Table 5.9 and for the earth model in Table 5.7. It can be seen that

the wavelet obtained at Pillbox borehole is different from that at Thorny Plantation

borehole (Table 5.4). Comparing the two sets of well logs (Figs. 3.20 and 3.21) and

lithology information (Figs. 3.17 and 3.18), there are no big differences in the four coal

seams apart from the small changes in the separation between the coal seams. Therefore, I

infer that the differences resulted from different noise contributions in the observed traces

at each borehole. Hence I regard the inverted wavelet at Thorny Plantation borehole as

being more reliable because the error energy is less. In the next section, I will show the

different inversion results obtained using these two different wavelets.
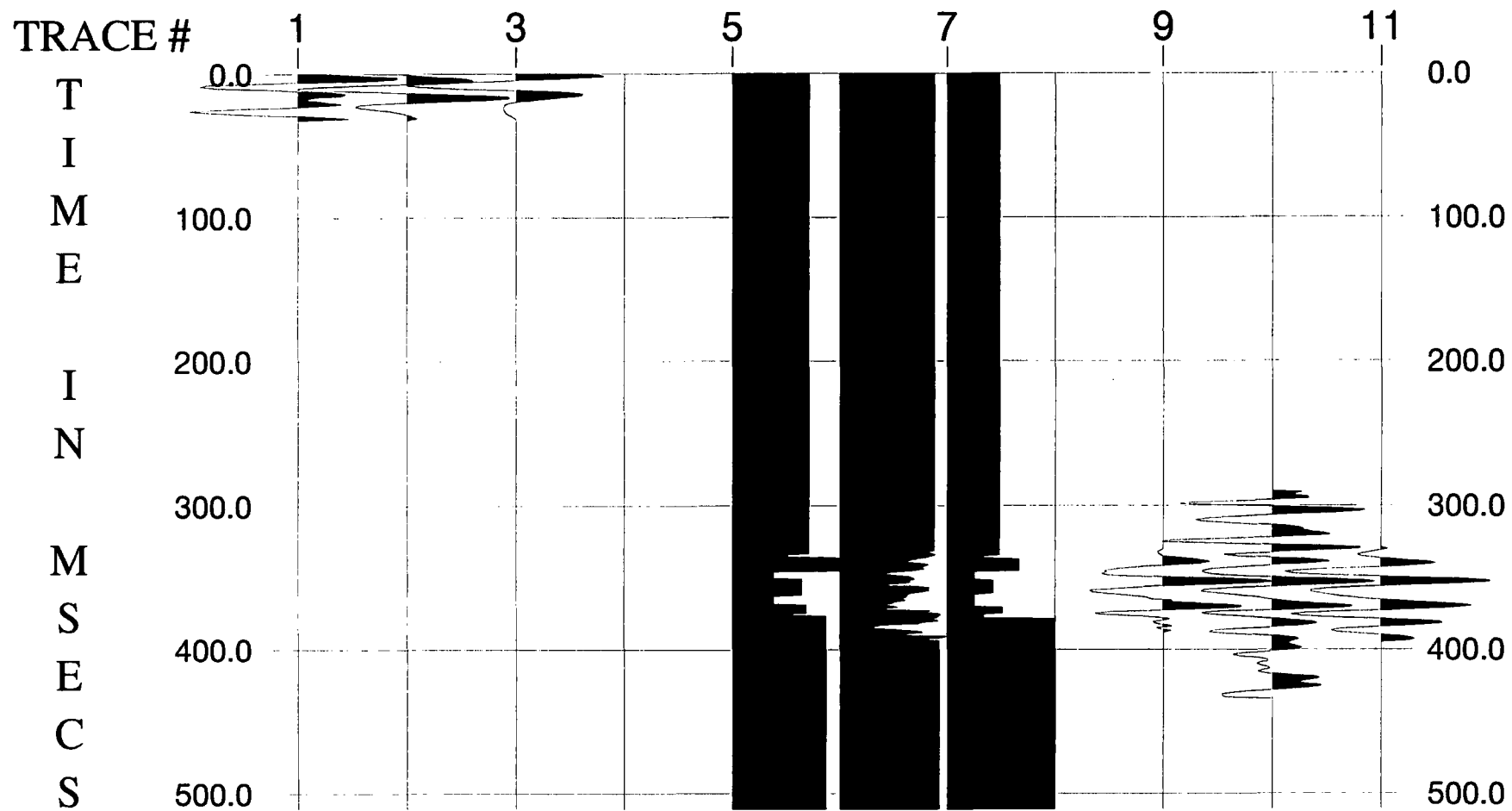
Figure 5.5b Inversion results for all parameters at CDP 1230, the nearest CDP to Pillbox borehole.

Using the initial guesses for the earth model (Table 5.7) and wavelet (Table 5.9), two iterations of the three stage GLI process were carried out, inverting successively for the boundary locations, acoustic impedance values, and wavelet parameters. The inversion results are listed in Table 5.10. The error energy and correlation coefficient for this inverted model are equal to 14.96% and 0.9365, respectively.

Wavelet	Bound. Locations. (ms)	Acous. Impedance. $(g/cm^3)(km/s)$	Ac. Imp. Gradients $(g/cm^3)(m/s^2)$
$f_1 = 21$ Hz		6.0	0.0
	372		
$f_2 = 51$ Hz		4.0	0.0
	375		
$f_3 = 67$ Hz		7.9	0.0
	385		
$f_4 = 143$ Hz		3.0	0.0
	390		
$a_0 = 2.8$		5.0	0.0
	401		
$\varphi_0 = -9$ degree		3.0	0.0
	407		
$\varphi_1 = -1.6$ deg./Hz		5.7	0.0
	413		
$\varphi_2 = 0.02$		4.0	0.0
	416		
$(degree/Hz^2)$		7.2	0.0

Table 5.10 Inversion results at Pillbox borehole

Figure 5.5b is the results of this procedure for the trace at CDP 1230. Trace (1) is the extracted wavelet. Trace (2) is the estimated wavelet after phase unwrapping. Trace (3) is the inverted wavelet. Trace (5) is the initial guess for the earth model. Trace (6) is the well log at Pillbox. Trace (7) is the inverted earth model. Trace (9) is the forward-modelled trace calculated from the extracted wavelet and the well logs. Trace (10) is the observed trace at CDP 1230. Trace (11) is the forward-modelled trace from the inverted wavelet and inverted earth model at CDP 1230.

5.4 Inversion for the Whole Section

5.4.1 Introduction

Theoretically, there should be no difference between inverting the data from either borehole to the other, if the parameters used and the inversion window are kept the same. However, it has been seen in the previous section that there are some differences in the initial guess wavelets and some parameters had to be fixed using a priori information when obtaining the initial guess earth models. It looks as though the quality of the data at Thorny Plantation is better than at Pillbox according to the error energy values and correlation coefficients. In order to see the effects of these differences, inversion for the whole section from each direction was carried out.

As can be seen in Fig. 3.14, the main coal seams are at 400 ms and 420 ms at CDP 994, but are significantly shallower at 350 ms and 370 ms at CDP 1230. Therefore, in order to keep the target seams within the inversion window, it is necessary to vary the location of the window along the section.

In order to get a stable solution for the nonunique inversion problem, it is better to fix some parameters and invert for a limited number of parameters by starting from the initial guess models (e.g. Table 5.2 and 5.4) rather than the inverted results at the borehole (e.g. Table 5.5) because of errors in the latter, as will be seen in the following sections. The following inversions were run for two iterations for each type of parameter (boundary locations, 8-parameter wavelet parameters) and two iterations for the overall inversion process.

When inverting the real data, there will be thickness changes for the coal seams. According to the study by Okaya (1995), in our situation, where the thicknesses of the coal seams are less than 10 ms in two-way time, the fundamental amplitude band (FAB) is only preserved between 20 - 150 Hz. Where the coal seam is very thin, i.e. 2 or 3 ms two-way time, the centre frequency of the FAB will be higher than 200 Hz (see Fig. 3 b, Okaya, 1995). The bandwidth of the processed data is 30 - 200 Hz (see §3.1.11) which means that there will be a very small amount of reflection energy with a very high frequency content present in the section when the thickness of a coal seam reduces to less than 3 ms.

In order to form the initial guess for the boundary locations at the next trace, after inverting the previous one, I adopt a combination method by taking the interpreted structural information (Martinez et al., 1992) into account together with the inversion results from the previous trace. The interpreted structural information was obtained by picking the two-way times of strong reflection events from the processed section. There are complementary selectable weighting coefficients between 0.0 to 1.0 for each of them which may be chosen as a result of trial-and error. For instance, if only the inversion results were used, the weighting coefficient will be 1.0 for the inversion results and 0.0 for the interpreted structural information.

5.4.2 From Thorny Plantation to Pillbox

I generally used the initial guess earth model and wavelet at Thorny Plantation borehole as the starting model (i.e. Tables 5.2 and 5.4) to invert the first trace at CDP 994. Inversion then proceeded as described above for the adjacent trace at CDP 995 onwards until reaching CDP 1230, which is the closest trace to Pillbox borehole. Tests indicated that the initial guess for the boundary locations was best obtained by applying equal weighting (coefficients 0.5) to the boundary locations obtained from inverting the previous trace and the boundary locations picking from the interpreted seismic section.
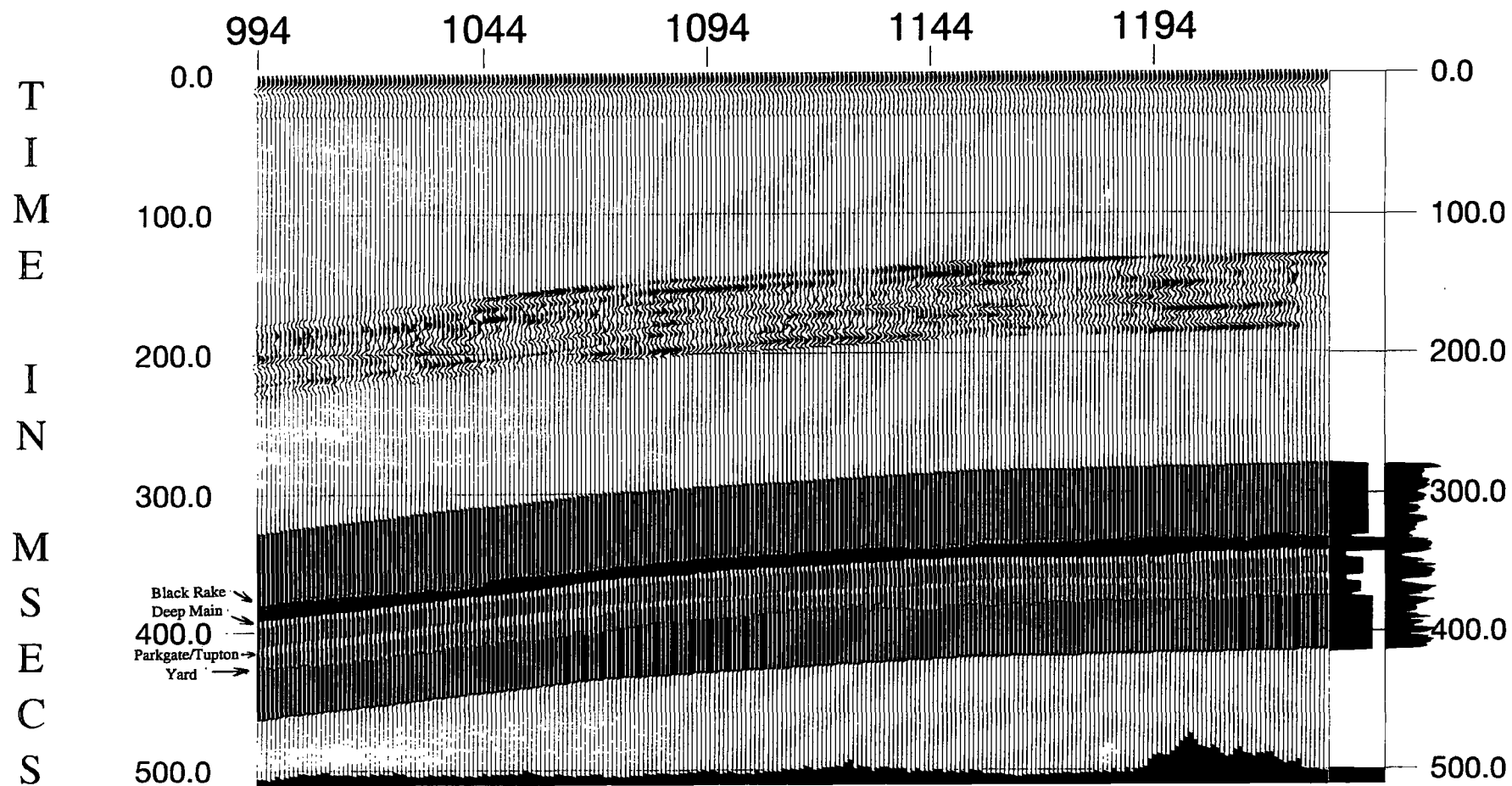
Figure 5.6a Inversion for boundary locations with the extracted wavelet obtained from Thorny Plantation borehole using 0.5/0.5 weights for establishing the initial guess model. The two traces on the right are the final inversion result at Pillbox borehole and (far right) the acoustic impedance function from the well logs. The boundary locations and the thicknesses of the main coal seams are almost matched.

Figure 5.6a shows the whole inverted section, in which I only inverted for the boundary locations by GLI, using equal weighting coefficients of 0.5 for the initial guess, and fixed the extracted wavelet and the acoustic impedance values (Table 5.2) along the section.

In order to see the changes of the wavelet along the sections (not the case in this processing), the inverted wavelet is plotted at the top of the trace for each inverted earth model at each CDP location in this figure and in the following ones. The difference between the observed trace and forward-modelled trace (obtained from the inversion result) in the window is also plotted above the earth model with a 200 ms time shift forward. The error energy is plotted below the inverted earth model at each CDP location as a vertical bar, indicating the reliability of the solution. The scale for the error energy is that the timing line at 500 ms corresponds to an error energy of 25 %.

From Fig. 5.6a, it can be seen that the first coal seam (Black Rake) has become very thin between CDP 1185 and CDP 1220 due to the very low reflection amplitudes (Fig. 3.14). At two areas in the middle of the section around CDP 1100 and CDP 1160, the thickness is greater than in other areas, which correlates with the reflection amplitudes on the migrated section.

The thickness of the Deep Main seam was fairly consistent across the whole section. It fluctuates in the vicinity of CDP 1200 and is a little bit thinner on isolated traces at CDPs 1123 and 1190. It can be seen from Fig. 3.14 that in those places the amplitudes of the reflection have decreased.

The thickness of the Parkgate/Tupton seam changes a lot according to the inversion. At first it stays unchanged until CDP 1075. Then it abruptly decreases in thickness by about a half until CDP 1200, which corresponds to an increase in frequency content and a decrease in amplitude of the reflection. Due to the low amplitude and poor continuity of the reflection from this coal seam between CDPs 1190 and 1220, the thickness is further
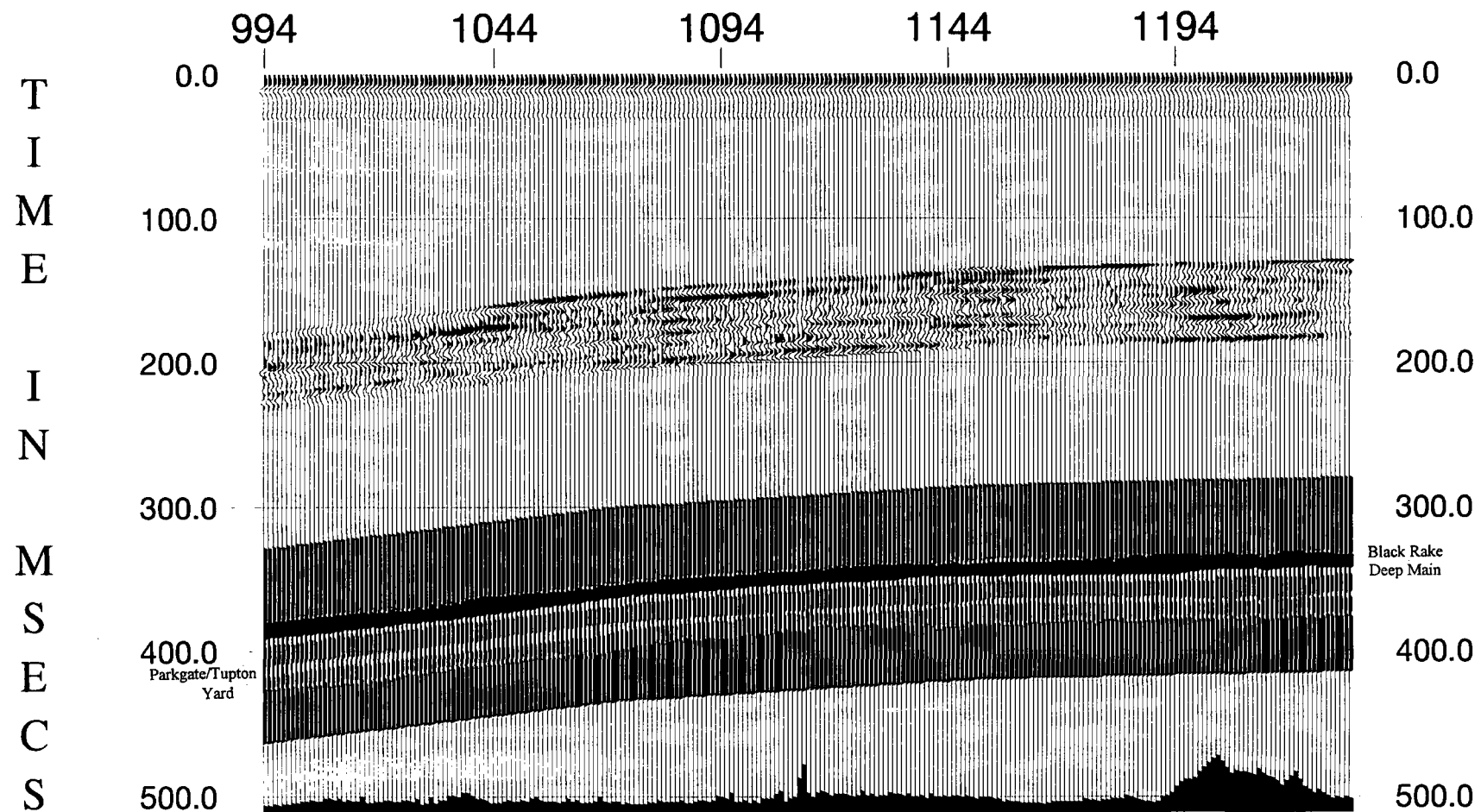
Figure 5.6b Inversion for boundary locations with the extracted wavelet obtained from Thorny Plantation borehole using 1.0/0.0 weights, i.e. initial guess based only on the interpreted structural information.
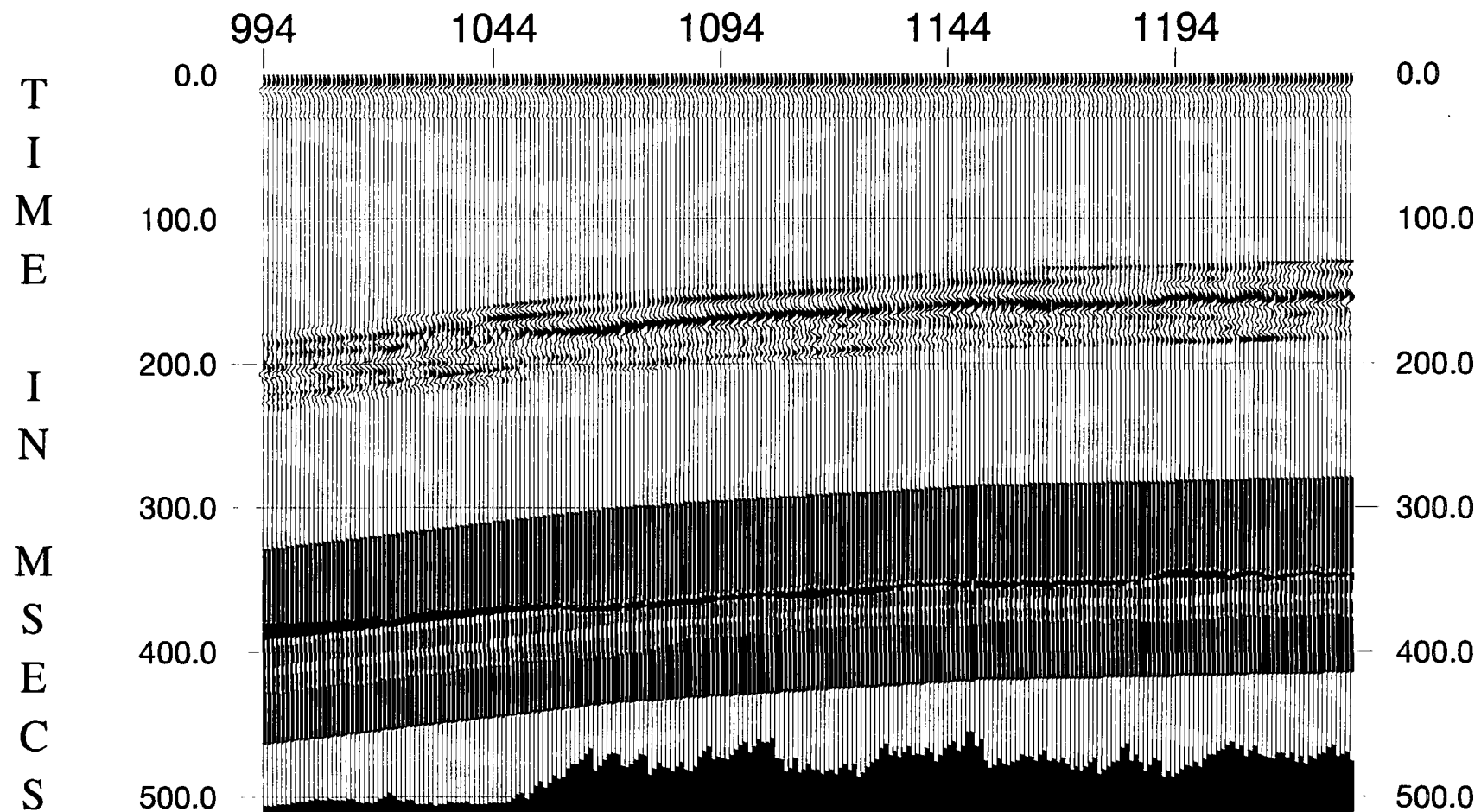
Figure 5.6c Inversion for boundary locations with the extracted wavelet obtained from Thorny Plantation borehole using 0.0/1.0 weights, i.e. initial guess based only on the previous trace inversion.

reduced to 1 - 2 ms. But when it reaches CDP 1230, i.e. the location of Pillbox borehole, it became thicker again.

The changes in thickness of the Yard seam also correspond to the reflection character on the processed section. Comparing the inversion results at the right hand side with the systematic studies at Pillbox, and noting the 38 ms time shift difference, the positions of the Black Rake, Deep Main, Parkgate/Tupton and Yard are all matched, but the thicknesses of the seams do not match the well log information at Pillbox (Fig. 3.22). This is because the reflection amplitudes of the observed traces are decreased a lot comparing with the started values at Thorny Plantation and the acoustic impedance values are fixed during this inversion procedure along the section.

Figure 5.6b is a similar inversion to Fig. 5.6a only differing in that the weighting coefficients were 1.0/0.0, i.e., the interpreted structural information was used and the inversion for each trace was totally independent, which is the current method used by other researchers (e.g. Brac et al., 1992). Comparing these two figures, there are no big differences between them. However it can be seen that the error energy at the middle of the section in Fig. 5.6a is a little bit less, and the inversion results look smoother than Fig. 5.6b in some areas.

Figure 5.6c shows the inversion results with 0.0/1.0 weighting coefficients, i.e., the inversion results for the boundary locations from the previous trace were used as the initial guess for the next trace. It can be seen that this method failed to trace the boundaries of these seams past CDP 1060 due to the phase changes on the observed trace. Because the errors in the inverted earth model parameters are reproduced in the initial guess for the next trace, the correct answer may not be obtained after inversion through a poor SNR area. The equal weighting coefficients, giving the results in Fig. 5.6a, are the best pair of those I have tested.
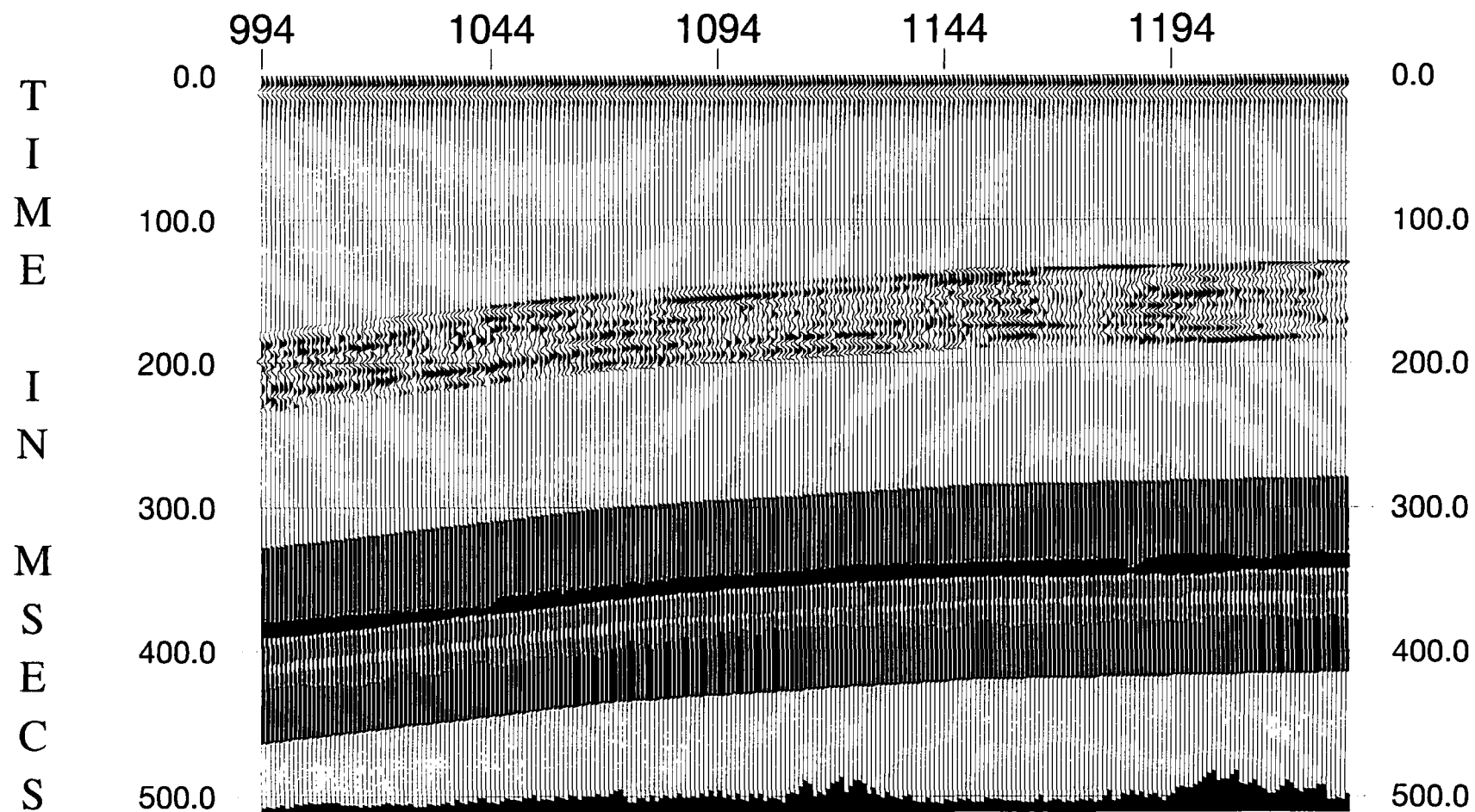
Figure 5.7a Inversion for boundary locations with 8-parameter wavelet of Table 5.4 and the initial guess earth model of Table 5.2.

Figure 5.7b Inversion for boundary locations and four frequency parameters with 8-parameter wavelet of Table 5.4 and the initial guess earth model of Table 5.2.
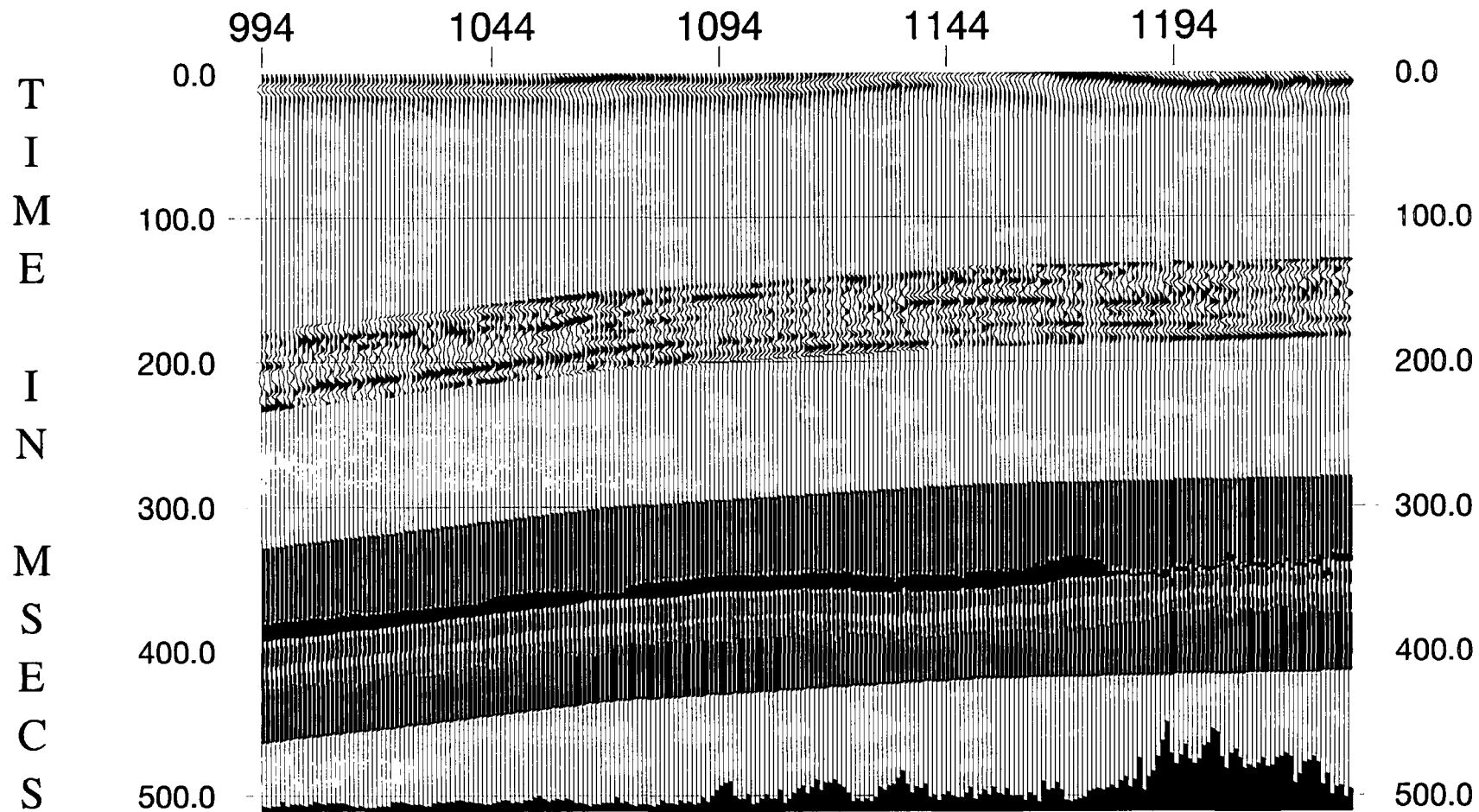
Figure 5.7c Inversion for boundary locations and all eight parameters with 8-parameter wavelet of Table 5.4 and the initial guess earth model of Table 5.2.

Figure 5.7d Inversion for boundary locations with the initial guess taken as the parameters shown in Table 5.5.

Figure 5.7a shows the results of inversion for the boundary locations with the 8-parameter wavelet and 0.5/0.5 weighting coefficients. The acoustic impedance values (Table 5.2) and the wavelet parameters (Table 5.4) were fixed. Because the extracted wavelet obtained from Thorny Plantation is quite accurate, due to the the good SNR there, the inversion with the 8-parameter wavelet was no better than Fig. 5.6a. The error energy values of the inversion in Fig. 5.7a are mostly larger than in Fig. 5.6a. In particular, the thickness of the Parkgate/Tupton seam varies more wildly.

Figuer 5.7b is the inversion result using an 8-parameter wavelet and inverting for boundary locations and four frequency parameters. It can be seen that it did a better job with the thickness changes of the Parkgate/Tupton seam, which looks more like Fig. 5.6a. It is interesting to see that the thick part of Parkgate/Tupton seam extended here to CDP 1105. Possibly this is because there is a frequency change in the data (see Fig. 3.14), which is allowed for by the inversion of Fig. 5.7b.

Figure 5.7c is the result of inverting for the boundary locations as well as all eight parameters of the wavelet. It is easy to see that the phase parameters do affect the boundary locations, especially in the poor SNR areas. It made the inversion solution unstable.

Fig 5.7d was obtained by using Table 5.5 as the initial guess model and inverting for boundary locations only. Comparing the result with Fig. 5.7a, there was no significant improvement anywhere. The acoustic impedance values around the Yard seam are unrealistically low, so it is difficult to see this seam on the section.

In order to show the stability of inverting for only the two main coal seams, I have tried to invert for the Deep Main and Parkgate/Tupton seams within the same window as the previous one. Figure 5.8a is the inversion for boundary locations with the extracted wavelet and 0.5/0.5 weighting coefficients. Even though the acoustic impedance values for
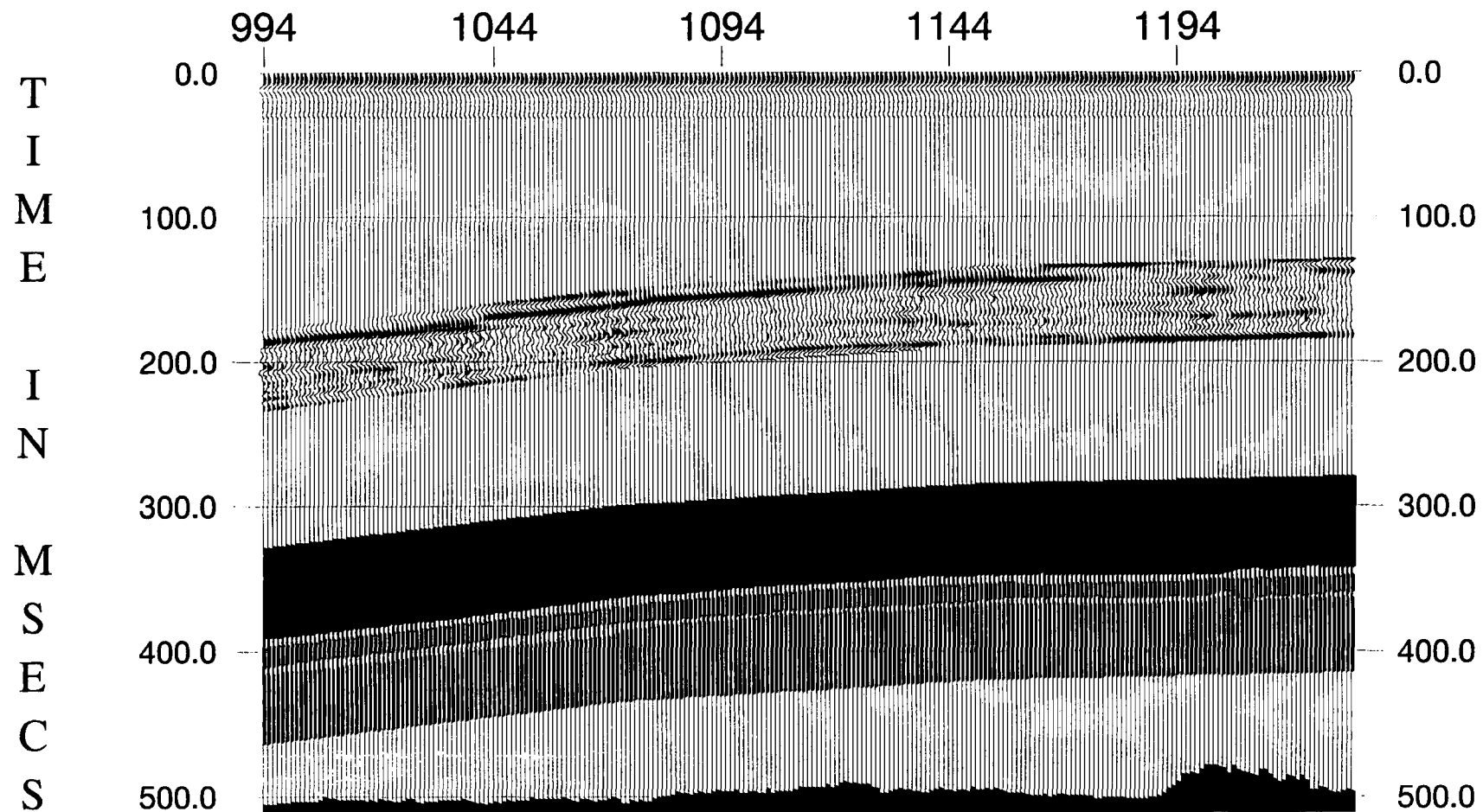
Figure 5.8a Inversion for boundary locations of the two main coal seams (the Deep Main and Parkgate/Tupton) with the extracted wavelet from Thorny Plantation borehole.
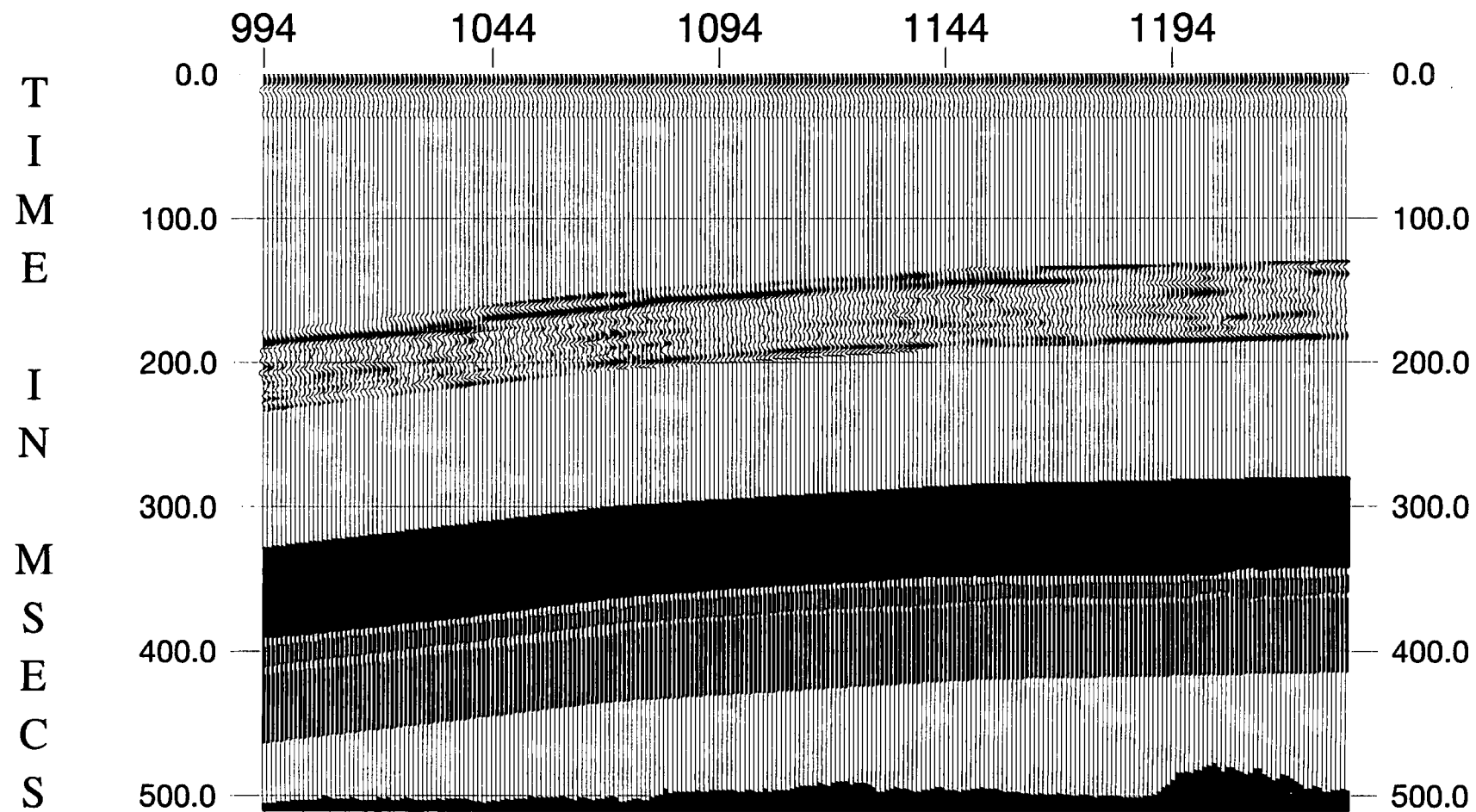
Figure 5.8b Same inversion as Fig. 5.8a except that twice as many iterations were applied.
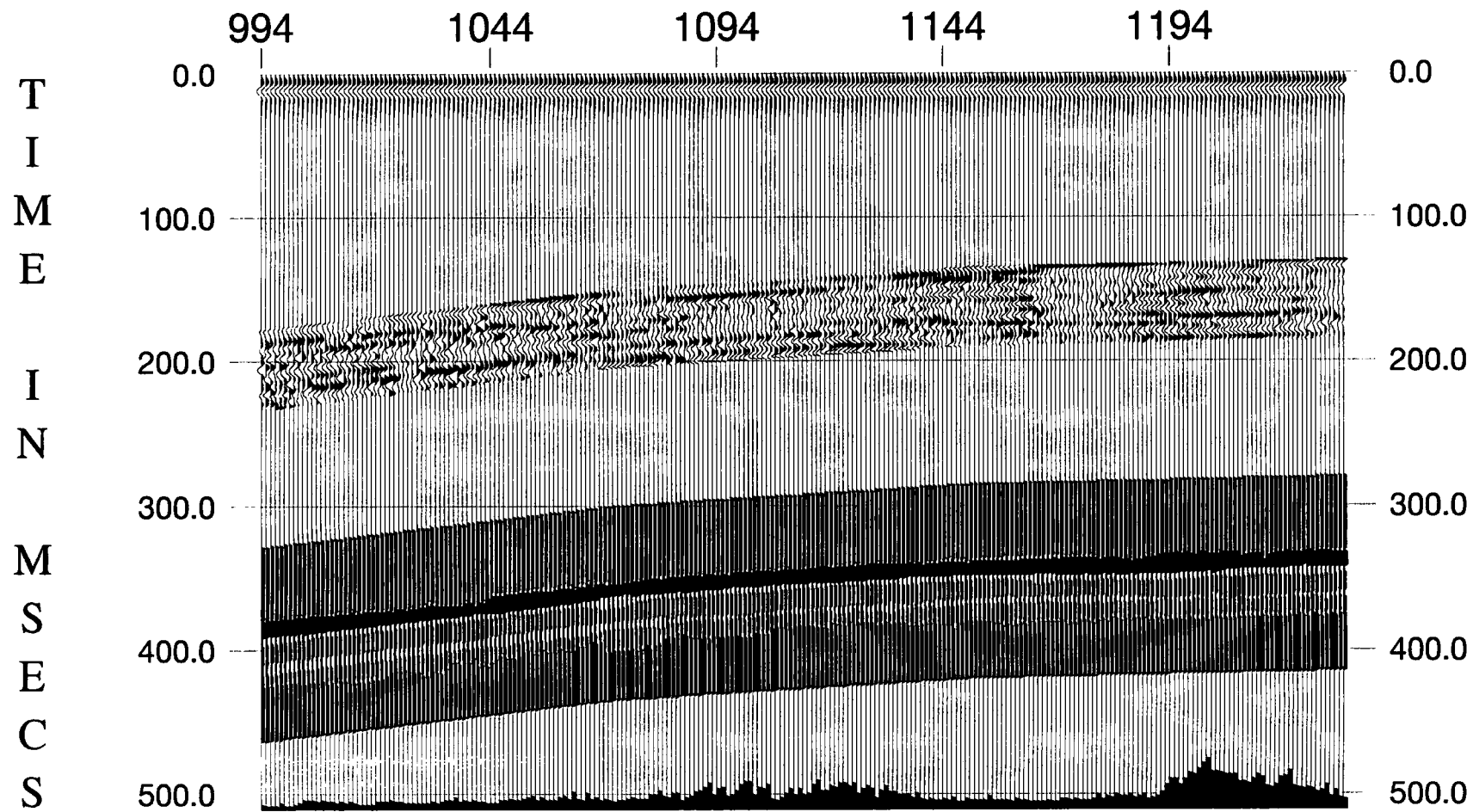
Figure 5.9a Inversion for boundary locations with the 7-parameter wavelet shown in Table 5.11.
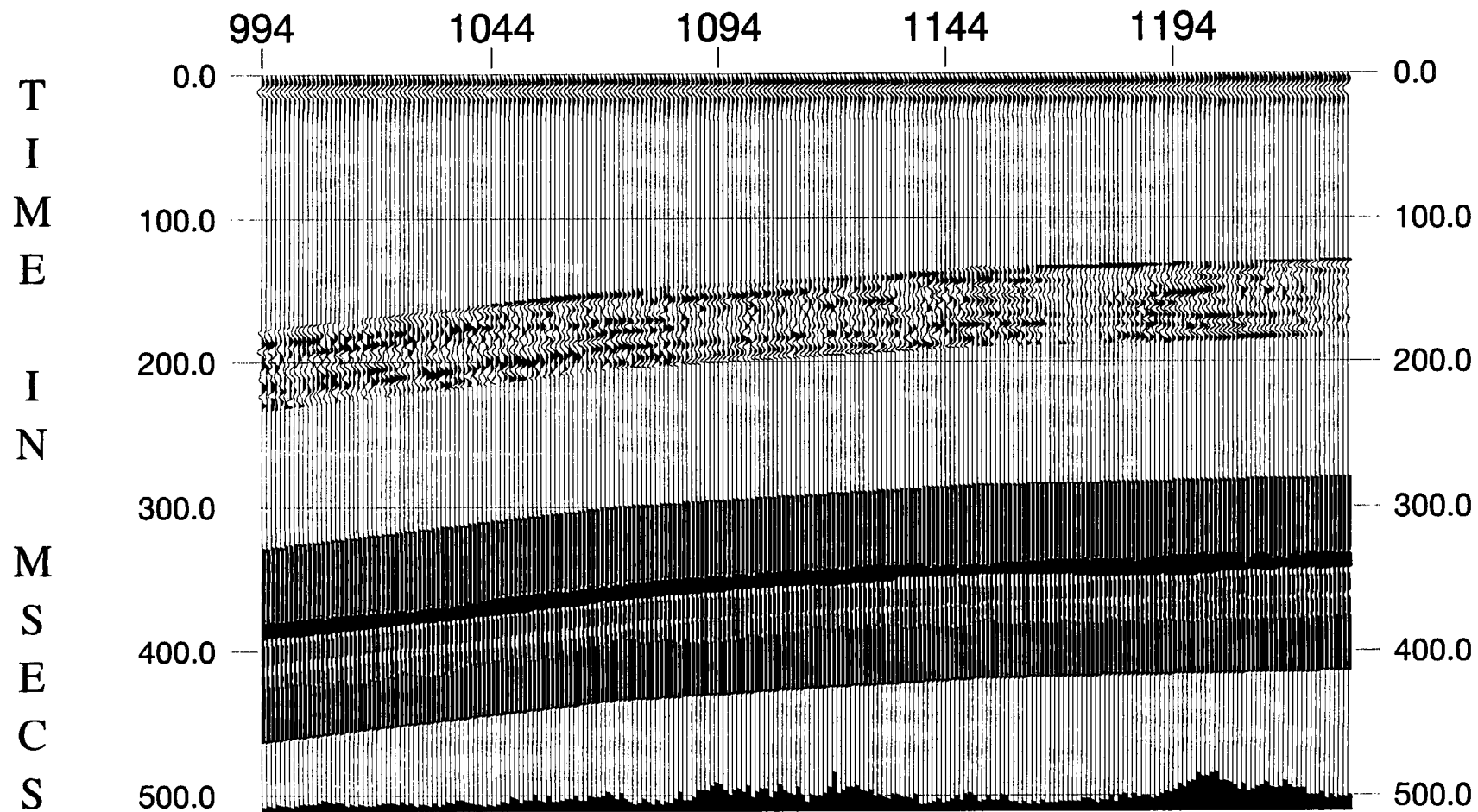
Figure 5.9b Inversion for boundary locations and four frequency parameters with the 7-parameter wavelet shown in Table 5.11.

the country rock were different from Table 5.2 and error energy values were a little bit bigger than Fig. 5.6a, the inversion results are almost the same in Fig. 5.6a. The error energy is bigger because only two coal seams were inverted within the same window. It can be seen that the trend of the error energy values is the same.

In addition to showing that sufficient iterations have been run to yield a stable result, I have tested an example with more than twice the number of iterations than used for Fig. 5.8a, i.e., a total of eight iterations were carried out. The results are shown in Fig. 5.8b. There is very little difference between them. This indicates the results obtained from Fig. 5.8a and Fig. 5.6a are stable.

Figure 5.9a is the inversion result starting with the same earth model (Table 5.2) and the 7-parameter wavelet, excluding φ_2, (Table 5.11) and inverting for the boundary locations. The result is quite different from that obtained using the 8-parameter wavelet (Fig. 5.7a), and it is difficult to say which one is better. However, it can be seen that the Deep Main seam has a more consistent thickness in Fig. 5.7a.

$f_1 = 16\,Hz$	$f_2 = 41\,Hz$	$f_3 = 52\,Hz$	$f_4 = 167\,Hz$
$a_0 = 5.83$	$\varphi_0 = 129$	$\varphi_1 = 2.14$	
	degree	degree/Hz	

Table 5.11 Initial guess model for 7-parameter wavelet

I also tried to invert for the boundary locations and the frequency parameters using a 7-parameter wavelet with the result shown in Fig.5.9b. It is very like the results of Fig. 5.7b obtained by using an 8-parameter wavelet, only differing in the extent of the thick part of the Parkgate/Tupton seam away from Thorny Plantation borehole, which looks better on Fig. 5.7b.
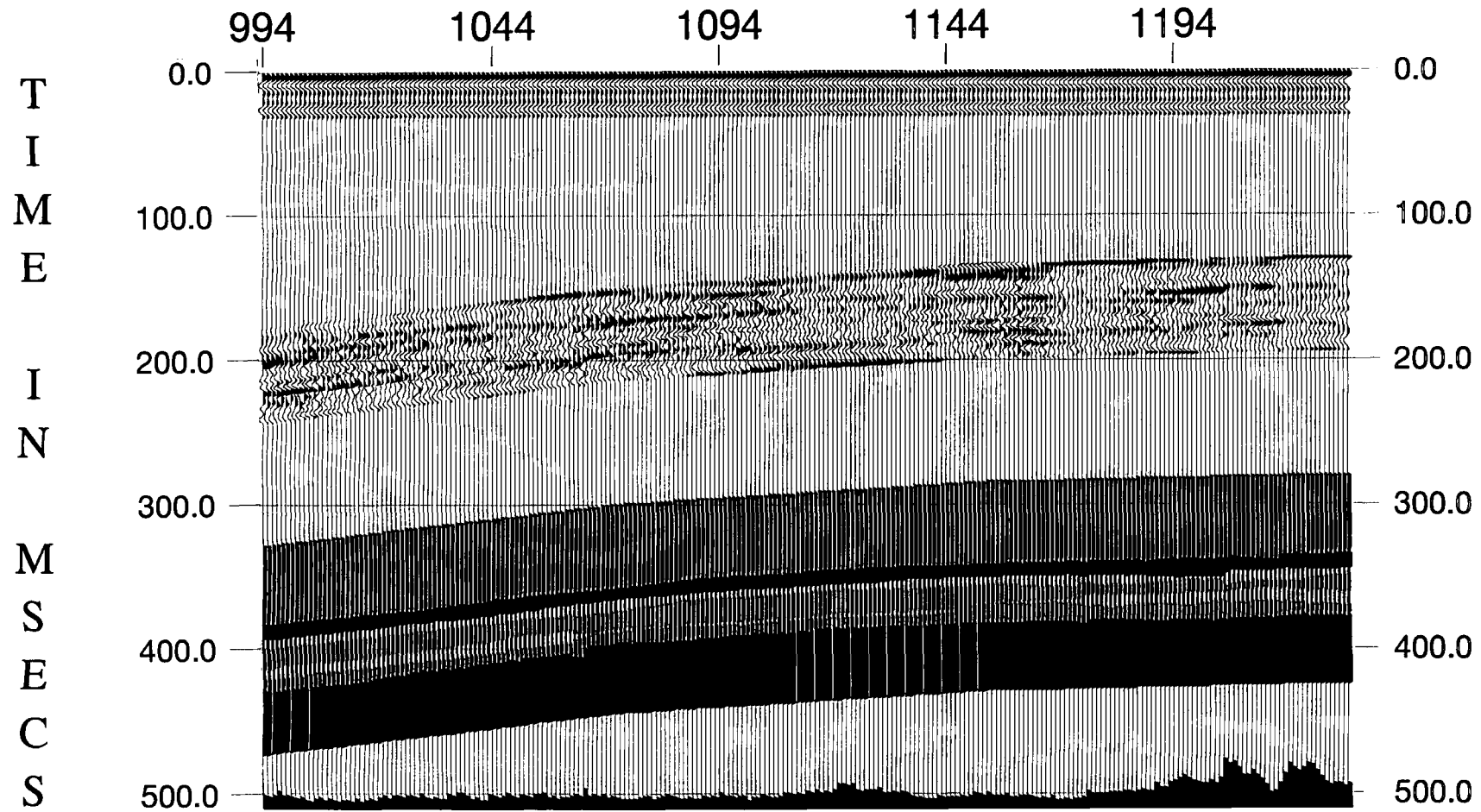
Figure 5.10a Inversion for boundary locations from Pillbox to Thorny Plantation with extracted wavelet obtained from Pillbox borehole and initial guess earth model of Table 5.7.
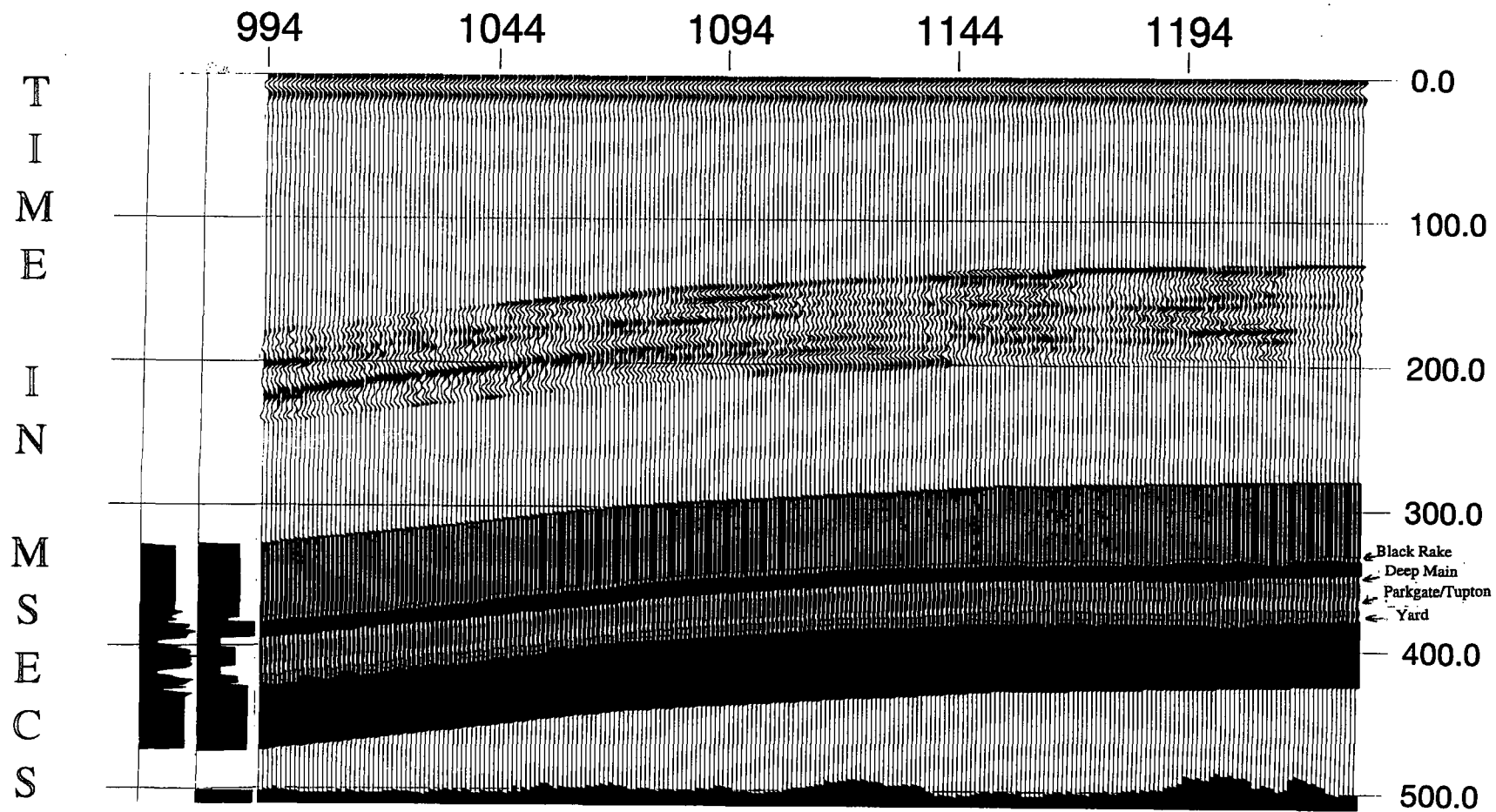
Figure 5.10b Inversion for boundary locations from Pillbox to Thorny Plantation with
8-parameter wavelet of Table 5.9 and initial guess earth model of Table 5.7. The two
traces on the left are the final inversion result at Thorny Plantation borehole and (far left) the
acoustic impedance function from the well logs. The boundary locations and the
thicknesses of the main coal seams are matched.
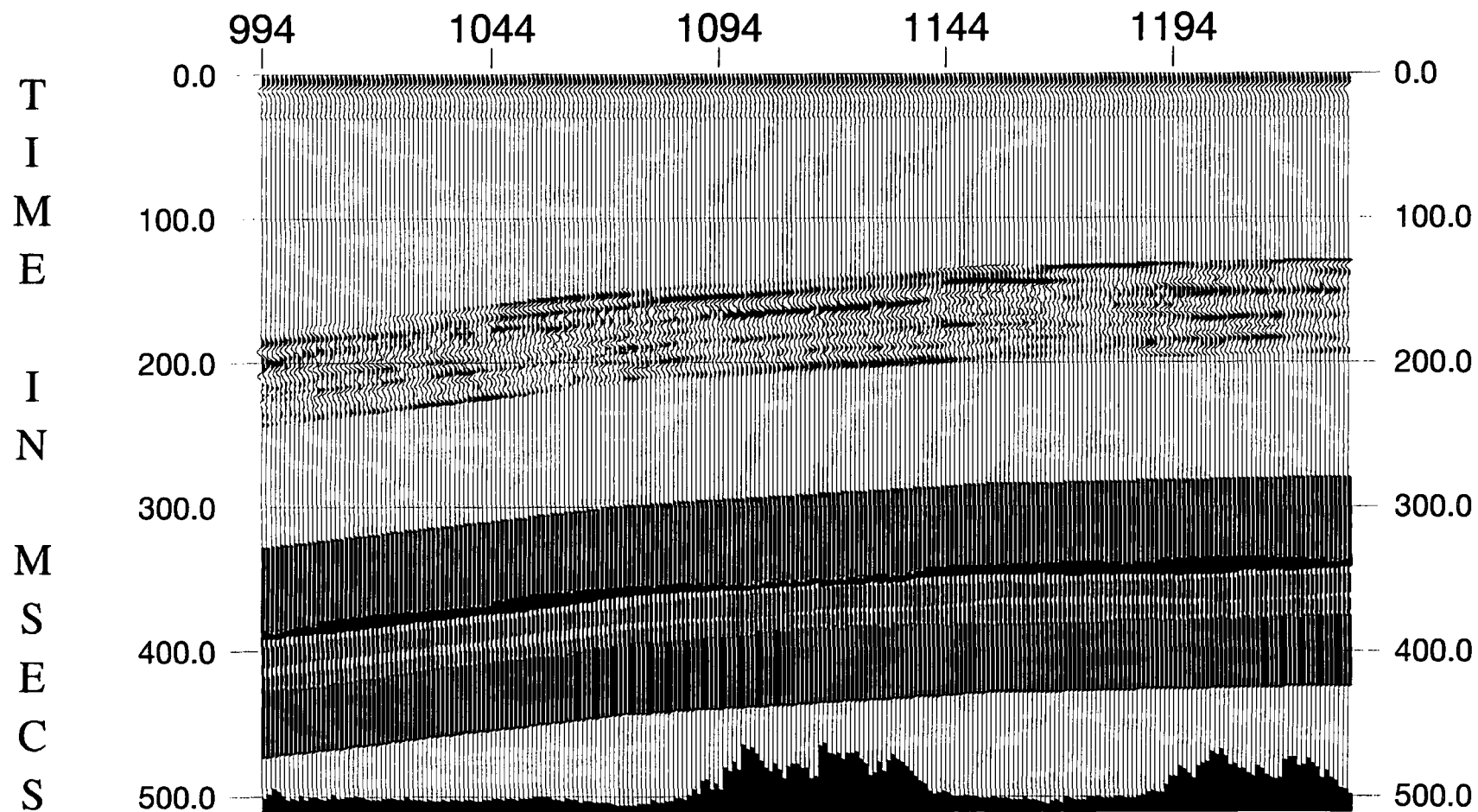
Figure 5.10c Inversion for boundary locations from Pillbox to Thorny Plantation with
the wavelet extracted from Thorny Plantation borehole and the same acoustic impedance
values as in Table 5.2.

5.4.3 From Pillbox to Thorny Plantation

Figure 5.10a is the result of inversion for the boundary locations with the extracted wavelet from Pillbox borehole starting at that borehole and moving progressively towards Thorny Plantation. The initial guess for earth model is shown in Table 5.7. As the extracted wavelet is quite different at Pillbox borehole, and the SNR is much lower for the initial guess, it is not surprising that the inversion result is much less smooth than Fig. 5.6a.

Figure 5.10b is the result of inversion with the 8-parameter wavelet (Table 5.9) instead of the extracted wavelet. From this inversion, the advantage of optimizing the wavelet parameter for the initial guess can be seen. The inversion result looks quite smooth and the error energy values are small, especially considering that the window was expanded by 10 time samples to take account of the large time shift (38 ms).

For the Black Rake seam, the thickness is greater than the previous inversion from Thorny Plantation to Pillbox. The reason is that in the initial guess (Table 5.7) the acoustic impedance contrast was lower than in Table 5.2. The thicknesses of the Deep Main and Parkgate/Tupton seams change smoothly apart from the poor SNR area at the right hand of the section. The Yard seam looks different possibly due to the effect of ten more samples being taken into the window. It is obvious that the boundary locations and the thicknesses of these seams at the two boreholes are different in the two sections (Fig. 5.6a and Fig. 5.10b) due to the different wavelets and different initial guesses for the earth model.

In order to remove these differences and to see whether the results are similar when the inversion is carred out in either direction, Fig. 5.10c shows the result of inversion for the boundary locations starting at Pillbox borehole and moving towards Thorny Plantation,
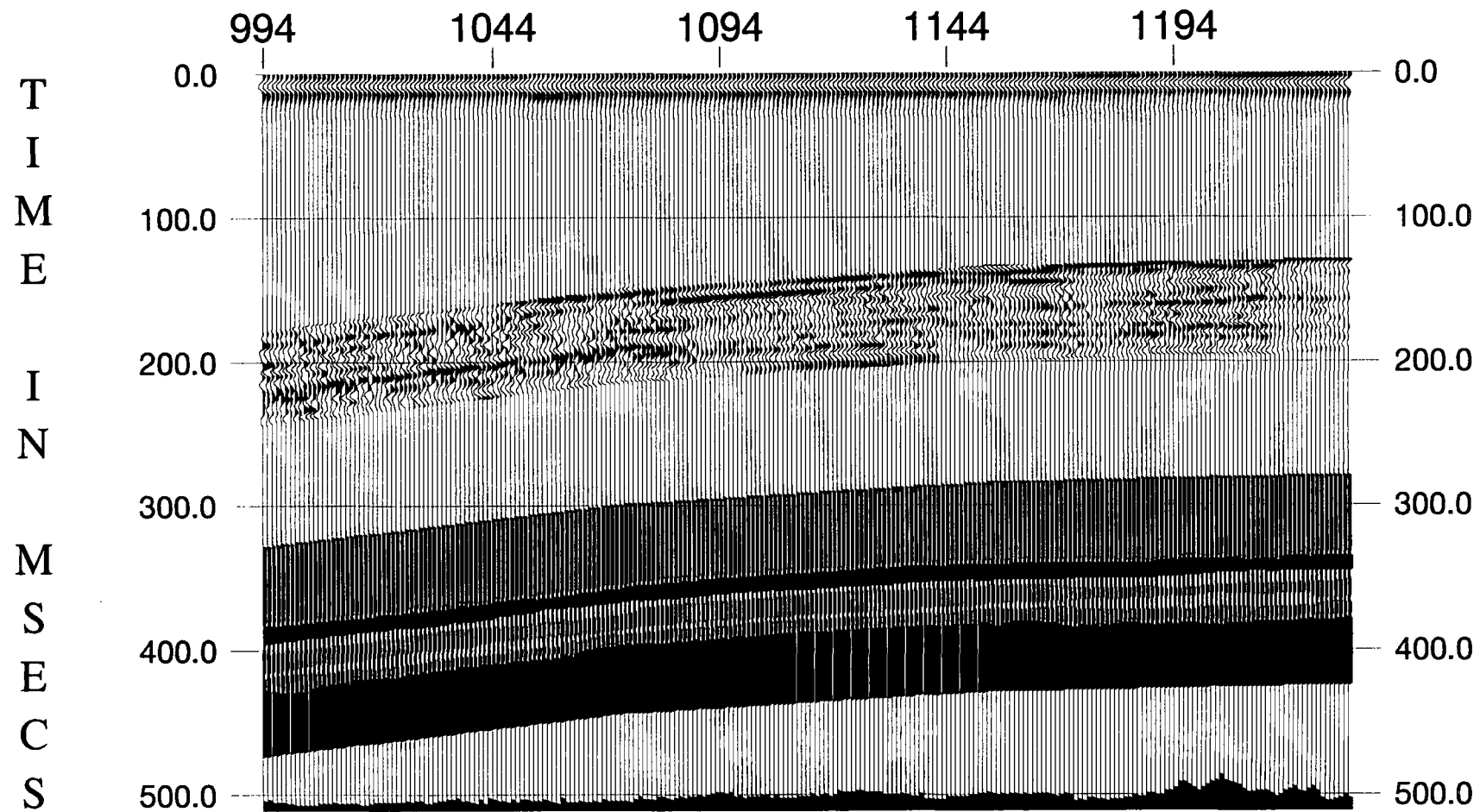
Figure 5.11a Inversion for boundary locations and four frequency parameters of the 8-parameter wavelet shown in Table 5.9.
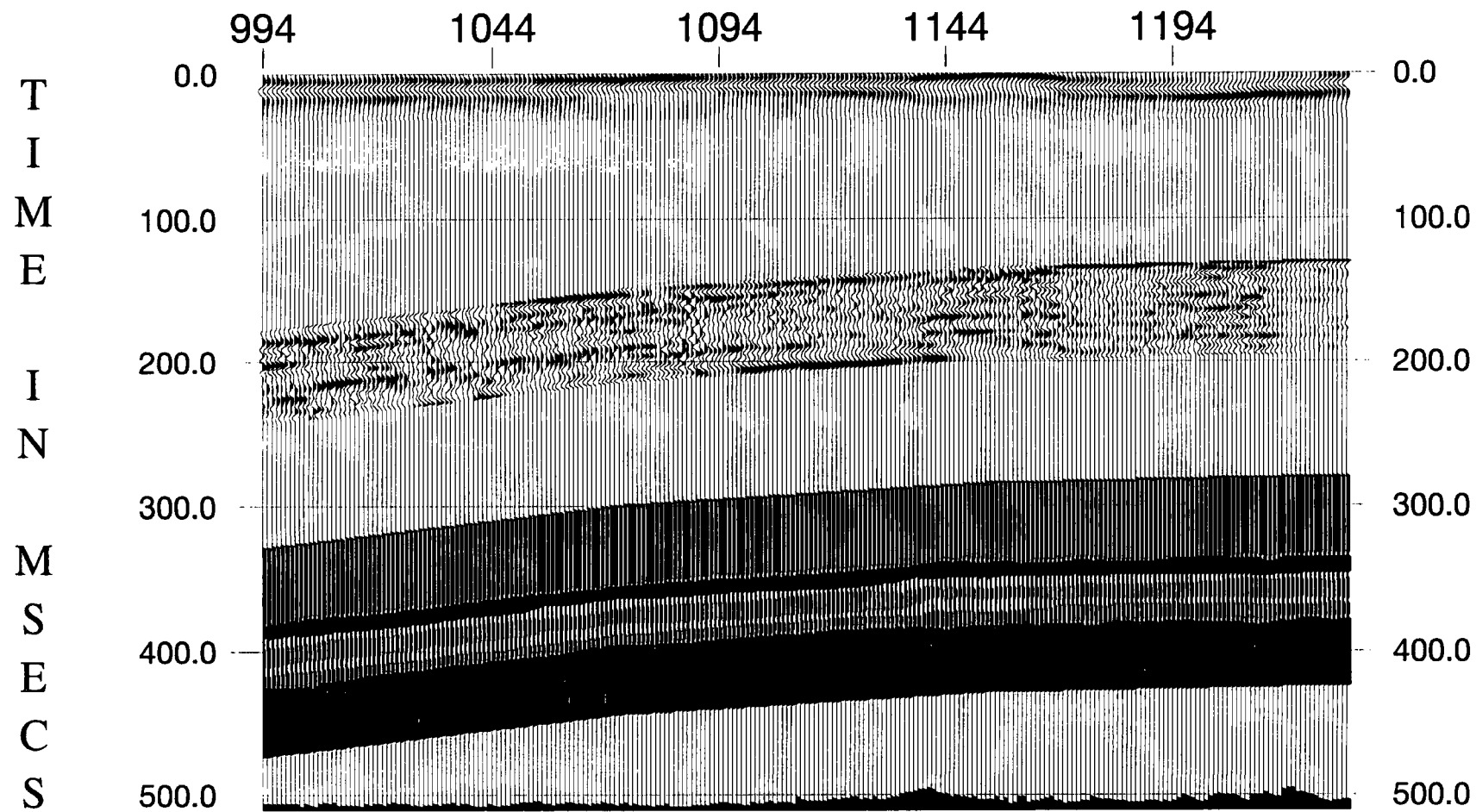
Figure 5.11b Inversion for boundary locations and all eight parameters of the 8-parameter wavelet shown in Table 5.9.

but using the wavelet extracted from Thorny Plantation and the acoustic impedance values from the initial guess earth model obtained from Thorny Plantation borehole (Table 5.2).

Comparing Fig. 5.10c and Fig. 5.6a, it can be seen that at the two boreholes the boundary locations and thicknesses of the two main seams (Deep Main and Parkgate/Tupton) are matched. The overall thickness variations of these two seams are similar except for the middle part and right hand end of the Deep Main due to the effect of the seam above and poor SNR area. Obviously the error energy values are quite different.

Figure 5.11a is the result of inverting for the boundary locations and the four frequency parameters of the 8-parameter wavelet (Table 5.9). At the right hand side, the behaviour of the Deep Main seam in Fig. 5.11a seems to be better than Fig. 5.10b. Figure 5.11b is the result of inverting for the boundary locations and all the 8 wavelet parameters. Again it can be concluded that the inversion for phase parameters and boundary locations together is no good, even though the error energy values tend to be very small.

5.5 Summary

The systematic studies at both boreholes are very important and very helpful for guiding the methodology for inversion along the section. They enabled a good initial guess to be found to start the inversion because the inversion result could be evaluated by comparison with the well logs. Sometimes it is necessary to make a compromise in parameter selection by choosing to fit either the boundary locations or the acoustic impedance values. The reason why this is necessary is because the amplitude values in a observed trace are not true relative amplitudes, i.e. the convolutional model is only an approximation for the traces on a processed section.

For the section used here, the inversion results are different when the inversion is carried out in opposite directions. The differences in the thicknesses of the coal seams are due to the extracted wavelets with different SNR from the observed data trace at each borehole.

When the extracted wavelet is inaccurate due to a poor observed trace near the borehole, the 8-parameter wavelet is quite a good approximation and useful for further inversion (Fig. 5.10b). Otherwise, the extracted wavelet is a better choice to use for the inversion. However, the disadvantage is that the extracted wavelet cannot sensibly be inverted along the section by GLI because it is described by too many parameters in the time domain and the inversion results would be unstable in the presence of noise.

It should be possible to obtain the thickness changes of coal seams by GLI with parameterization if good SNR data with true relative amplitude values are available. and if it is valid to assume that the acoustic impedance values are constant along the section. However, the difficulty in practice is to get a processed section with true relative amplitude values.

6 Conclusions and Suggestions for Future Work

6.1 Conclusions

From the work described here, it can be seen that my improved iterative method for applying GLI has potential for obtaining the thickness variations of the coal seams from migrated seismic data in the Coal Measures. Processing must produce true relative amplitude of events on the migrated section in order to obtain the correct answer for the thicknesses of the coal seams. Since this is the first time that GLI has been applied to seismic data from the Coal Measures, particular points concerning the inversion method should be noted as follows:

1.   For simplification, it is possible to parameterize the country rocks between the coal seams (normally interbedded sandstones and siltstones) as uniform layers, which helps to make the problem stable and reduce the degree of non-uniqueness. Well log information is necessary for establishing the initial guess model; otherwise it is most unlikely that the global minimum will be found.

2.   The extracted wavelet obtained as a Wiener shaping filter at the borehole can be fixed or inverted as an 8-parameter wavelet defined in the frequency domain. When the wavelet extraction is based on an observed trace with a poor SNR, the 8-parameter wavelet in the frequency domain will be advantageous as it can subsequently be optimized by iterative inversion with the earth model parameters at the borehole. The parameters of the 8-parameter wavelet should be fixed after inversionat the borehole in order to avoid the interference with the boundary locations.

3. Due to nonlinearity, the method used for determining the boundary locations must take into account the potential interference from other parameters, i.e the acoustic impedance values and the wavelet parameters. In the real-data example shown, for the initial guess of the boundary locations for each trace, it was better to combine the results from inversion of the previous trace inversion with structural interpretation of the migrated section.

4. Systematic studies at boreholes are essential to work out which are the dominant coal seams, to decide what wavelet should be used for the inversion, and to establish the initial guess model. Seismic data processing must be done very carefully to produce the true relative amplitude reflections, and the systematic studies at the boreholes reveal the extent to which this has been achieved.

5. In the inversion for thin beds in the Coal Measures, it is useless to invert for all the earth model and wavelet parameters by GLI, because they interfere with each other and make the problem highly non-unique. Even though I succeeded in carrying it out with the synthetic examples, many other factors are involved in real data. It is desirable to try to put some constraints on the acoustic impedance values in the inversion, as described by Oldenburg (1986), to ensure that a unique solution is obtained for the thicknesses of the coal seams.

6. Unsurprisingly, it is more stable to invert the migrated section starting at a borehole where the nearest observed trace has a higher SNR. I have shown that, even with the same extracted wavelet and the same initial guess for the acoustic impedance values, there are still some differences between the inversion results obtained from different directions. This is because during the construction of the initial guess model for each trace, the inversion results from the previous trace were taken into account.

7. If the initial guess is based on structural interpretation, GLI can work through poor SNR areas and get a reasonable answer at the end of the section. This is difficult to achieve when only the inversion result from the previous trace is used as the initial guess model for the current trace. The combination of both sources of information for making the initial guess appears to give better results than using either source on its own.

6.2 Suggestions for Future Work

If the inversion result from previous trace is used for, or at least contributes to, the initial guess for the current trace, it has been shown that the inversion produces different results when carried out in opposite directions. That needs to be investigated by some 2-D synthetic models, e.g. to see whether splitting of coal seams will affect this. The observed effect is the well known problem in inversion that the result can easily end up at a local minimum if the starting model is too far from the global minimum.

If possible, it would be desirable to process another dataset which has better SNR and known geological features, i.e., having been mined since the seismic data were accquired.

A new data processing procedure should be developed in order to get true relative amplitude values for the Coal Measures. It would require a more complicated forward model to take proper account of multiple activity instead of the simple convolution model; however, it would dramatically increase the cost of the computation work.

References

Aki, K., 1981, 3-D inhomogeneities in the upper mantle. Tectonophysics, 75, 31-40.

Aki, K. and Richards, P. G., 1980, Quantitative Seismology, Vols 1 and 2. W. H. Freeman and Company.

Al-Sadi, H. N., 1980, Seismic Exploration, Berkhauser Verlag, Basel.

Archer, S. H., King, G. A. and Uden, R. C., 1993, An integrated approach to reservoir characterization using seismic and well data. 5th EAPG Conference, Extended Abstracts, F003.

Ausburn, B. E., 1977, Well log editing in support of detailed seismic studies. Transactions of the SPWLA 18th Annual Logging Symposium, Paper F.

Backus, G. E. and Gilbert, J. F., 1967, Numerical application of a formalism for geophysical inverse problems. Geophys. J. R. astr. Soc., 13, 247-276.

Backus, G. E. and Gilbert, J. F., 1968, The resolving power of gross earth data. Geophys. J. R. astr. Soc., 16, 169-205.

Bamberger, A., Chavent, G., Hemon, C. and Lailly, P., 1982, Inversion of normal incidence seismograms. Geophysics, 47, 757-770.

Beylkin, G., 1984, The inversion problem and application of the generalized Radon transform. Comm. Pure & Applied Math., 37, 579-599.

Bleistein, N., Cohen, J. K. and Hagin, F. G., 1985, Computational and asymptotic aspects of velocity inversion. Geophysics, 50, 1253-1265.

Brac, J., Dequirez, P. Y., Herve, F., Jacques, C., Lailly, P., Richard, V. and Nhieu, D. T. van, 1992, Inversion with a priori information: an approach to integrated stratigraphic

interpretation. Reservoir Geophysics, R. E. Sheriff (ed.), 251-258. Society of Exploration Geophysicists.

Bracewell, R., 1978, The Fourier Transform and Its Applications. McGraw-Hill Book Co.

Cardy, S., 1995, Make or break year for coalbed methane. Petroleum Review, February issue, 80-82.

Chen, Y. M., 1985, Generalized pulse-spectrum technique. Geophysics, **50**, 1664-1675.

Claerbout, J. F., 1985a,Fundamentals of Geophysical Data Processing. McGraw-Hill Book Co.

Claerbout, J. F., 1985b,Imaging the Earth's Interior. Blackwell Scientific Publications.

Cohen, J. K. and Bleistein, N., 1979, Velocity inversion procedure for acoustic waves. Geophysics, **44**, 1077-1087.

Cooke, D. A., 1981, Generalized linear inversion of seismic data. M. Sc. thesis. T-2459, Colorado School of Mines, Golden.

Cooke, D. A. and Schneider, W. A., 1983, Generalized linear inversion of reflection seismic data. Geophysics, **48**, 665-676.

Cornish, B. E. and King, G. A., 1988, Combined interactive analysis and stochastic inversion for high-resolution reservoir modeling, 50th EAEG Meeting Abstracts, 104.

Creel, J. C., 1995, Potential for the development of UK coalbed methane. Petroleum Review, February issue, 74-77.

Dahl, T. and Ursin, B., 1991, Parameter estimation in a one-dimensional anelastic medium. Journal of Gephysical Research, **96**, 20,217-20,233.

Dines, K. A. and Lytle, R. J., 1979, Computerized geophysical tomography. Proceedings of the IEEE, **67**, 1065-1072.

Dresen, L. and Ruter, H., 1994, Seismic Coal Exploration, Part B: In-Seam Seismics. Pergamon.

Fairbairn, C. M., Holt, J. M. and Padget, N. J., 1986, Case histories of the use of the surface seismic method in the UK coal mining industry. Coal Geophysics, SEG Geophysics reprint series No. 6, D. J. Buchanan and L. J. Jackson (eds), 188-203. Society of Exploration Geophysicists.

Gochioco, L. M., 1992, Modeling studies of interference reflections in thin layered media bounded by coal seams. Geophysics, 57, 1209-1216.

Goupillaud, P. L., 1961, An approach to inverse filtering of near-surface layer effects from seismic records. Geophysics, 26, 754-760.

Graebner, R., Wason, C. and Meinardus, H., 1981. Three-dimensional methods in seismic exploration. Science, 211, 535-540.

Hartley, H. O., 1961, The modified Gauss-Newton method for fitting of non-linear regression functions by least squares. Technometrics 3, 269-280.

Lavergne, M. and Willm, C., 1977, Inversion of seismograms and pseudo velocity logs. Geophysical Prospecting, 25, 231-250.

Lindseth, R. O., 1979, Synthetic sonic logs - a process for stratigraphic interpretation. Geophysics, 44, 3-26.

Lines, L. R. and Treitel, S., 1984, Tutorial: A review of least-squares inversion and its application to geophysical problems. Geophysical Prospecting, 32, 159-186.

Marquardt, D. W., 1963, An algorithm for least-squares estimation of nonlinear parameters. J. Soc. Indust. App. Math., 11, 431-441.

Martinez, R. D., Cornish, B. E., Rebec, A. J. and Curtis, M. P., 1992. Complex reservoir characterization by multiparameter constrained inversion. Reservoir Geophysics, R. E. Sheriff (ed.), 224-234. Society of Exploration Geophysicists.

Mazzotti, A. and Mirri, S., 1988, An experience in seismic amplitude processing. First Break, 9, 65-73.

Miller, D., Oristaglio, M. and Beylkin, G.,1987, A new slant on seismic imaging: migration and integral geometry. Geophysics, **52**, 943-963.

Newman, P., 1973, Divergence effects in a layered Earth. Geophysics, **38**, 481-488.

Okaya, D. A., 1995, Spectral properties of the earth's contribution to seismic resolution. Geophysics, **60**, 241-251.

Oldenburg, D. W., Scheuer, T. and Levy, S., 1983, Recovery of the acoustic impedance from reflection seismograms. Geophysics, **48**, 1318-1337.

Oldenburg, D. W., Levy, S., and Stinson, K., 1986, Inversion of band-limited reflection seismograms: theory and practice. Proc of Inst. Elect. Electr. Eng., **74**, 487-497.

Oppenheim, A. V. and Schafer, R. W., 1975, Digital Signal Processing, Prentice-Hall.

Pan, S. X. and Kak, A. C., 1983, A computational study of reconstruction algorithns for diffraction tomography. IEEE Trans. Acous. Speech Sig. Proc., **ASSP-31**, 1262-1275.

Poggiagliolmi, E., Berkhout, A. J. and Boone, M. M., 1982, Phase unwrapping: possibilities and limitations. Geophysical Prospecting, **30**, 281-291.

Pratt, R. G. and Goulty, N. R., 1991, Combining wave-equation imaging with traveltime tomography to form high-resolution images from crosshole data. Geophysics, **56**, 208-224.

Raymer, L. L. and Burgess, K. A., 1980, The role of well logs in reservoir modelling. 55th SPE/AIME Annual Meeting, SPE 9342.

Redanz, M., 1988, Acoustic impedance from least-squares inversion of reflection seismograms. 50th EAEG Meeting, Abstracts, 108.

Robinson, E. A. and Treitel, S., 1980, Geophysical Signal Analysis. Prentice-Hall.

Robinson, E. A., 1983, Seismic Velocity Analysis and the Convolutional Model. International Human Resources Development Corpn.

Sabatier, P. C., 1977a, Positivity constraints in linear inverse problems--I. General theory. Geophys. J. R. astr. Soc., **48**, 415-441.

Sabatier, P. C., 1977b, Positivity constraints in linear inverse problems--II. Applications. Geophys. J. R. astr. Soc., **48**, 443-459.

Sen, M. K. and Stoffa, P. L.,1991, Nonlinear one-dimensional seismic waveform inversion using simulated annealing. Geophysics, **56**, 1624-1638.

Shafer, R. W., 1969, Echo removel by discrete generalized linear filtering. Research Laboratory of Electronics, Massachusetts Institute of Technology, Technical Report No. 466.

Shatilo, A. P., 1992, Seismic phase unwrapping: methods, results, problems. Geophysical Prospecting, **40**, 211-225.

Sheriff, R. E. and Geldart, L. P., 1983, Exploration Seismology, Vol. **2**: Data Processing. Cambridge University Press.

Stoffa, P. L. and Sen, M. K.,1991, Nonlinear multiparameter optimization using genetic algorithms. Inversion of plane-wave seismograms. Geophysics, **56**, 1794-1810.

Tarantola, A. and Valette, B., 1982, Generalized nonlinear inverse problems solved using the least squares criterion. Rev. Geophys. Space Physics, **20**, 219-232.

Treitel, S. and Robinson, E. A., 1966, Seismic wave propagation in layered media in terms of communication theory. Geophysics, **31**, 17-32.

Van Riel, P. and Berkhout, A. J., 1985, Resolution in seismic trace inversion by parameter estimation. Geophysics, **50**, 1440-1455.

Weber, Z., 1986, One-dimensional linear inversion of reflection seismic data. Model Optimization in Exploration Geophysics, Andreas Vogel (ed.), Proceedings of the 4th International Mathematical Geophysics Seminar, 269-290. Vieweg, Braunschweig.

White, J. E. and Sengbush, R. L., 1987, Production Seismology. Geophysical Press.

Widess, M. B., 1973, How thin is a thin bed? Geophysics, **38**, 1176-1180.

Wiggins, R. A., Larner, K. L. and Wisecup, R., 1976, Residual statics analysis as a general linear inverse problem. Geophysics, **41**, 922-938.

Yilmaz, O., 1987, Seismic Data Processing. Society of Exploration Geophysicists.

Yu, G., 1985, Offset-amplitude variation and controlled-amplitude processing. Geophysics, **50**, 2697-2708.

Ziolkowski, A. and Lerwill, W. E., 1979, A simple approach to high resolution seismic profiling for coal. Geophysical Prospecting, **27**, 360-393.

Appendix   Computer Software

This appendix gives a brief outline of a GLI inversion using the program available in University of Durham, and also lists the few programs and subroutines that I have written. External subroutines include NAG Fortran subroutines and UNIRAS plotting library. Some programs that have merely been altered by me for use with data plotting are not listed here.

All programs are written in Fortran 77 to run on a HP or a Sun4. The input parameters in the data file at the head of each program should be checked and altered to suit the needs of the user.

CC This is a input data file for the main program indd to carry out a GLI method   CC

```
tg,egy1,749,279,-1,279,279,9,a,pb2.dat   (fl,nl,am0,am1,nm2,nmw,alm,fit)
aaa.dat,gaal.dat,result1,12.0,5.0,0.2,2,492,8.0,5.0.5  (ffl,ff2,ff3,ea,em,ga,lp,wisi,wipi)
y,3,28,35,.0001,  (GLI wavelet inversion:fif,ig0,mfl,mf2,almda)
0,0,0,0,0,0,0,0,  (fixed or inverted)
n,1,331,395,1.,  (location inversionin time:ftg,ig1,mg1,mg2,almda00)
y,2,1,9,.01,   (location inversion in frequency:fm,in1,mn1,mn2,almda11)
0,0,0,0,0,0,0,0,9,0,0,0,0,0,15,0,0,0,19  (fixed or inverted)
y,1,10,18,.001, (acoutic impedance inversion:fih,ih1,mh1,mh2,almda22)
0,11,0,13,0,15,0,17,0,19,20,0,22,0,24,0,26,27, (fixed or inverted)
n,2,19,27,.01, (gradients of acoustic impedance:fti,iil,mil,mi2,almda33)
19,20,0,22,0,24,0,26,27, (fixed or inverted)
y,1,30,33,.0001, (wavelet inversion in F-domain:fij,ij1,mj1,mj2,almda44)
28,29,0,0,0,0,34,35 (fixed or inverted)
5,3,14,9,17,9,11,3,96
0.001,.512,32,9,2,9,40,0,0. (dt,lt,iwk,an,iq,mm,lk,itj,akp)
.372,.374,.384,.389,.401,.407,.414,.415,.512
5.5,4.0,7.7,3.0,5.0,3.0,5.3,4,.6.7,4,.7.6,4,.7.6,4,.7.6,4,.7.6,4,.7.6,
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
100.,-.10,25,.35,.85,.150,.0.,0.
```

```
C*************************  MAIN PROGRAM  *************************

      complex w(1024),w2(1024),w3(1024)
      common /wavelet/dt/ddd,de,dg,dp,ds,df,dad,lp,ga,ea,em
      parameter(jt=1024,jp=1024,ji=40,ap=10)
      dimension r(jt),e1(jt),r1(jp),lista(jp),f2(jt),pf2(ap),ifix(jp),
     *error(50),rr(jp),e3(jt),e0(jp),g1(jt),pf1(ap),r2(jp),a(jt),y1(jt)
      dimension cova(jp,jp),alpha(jp,jp),iti(jt),r4(jp),f(jt),r3(jp)
     * ,aok(jp),e(jt),aaee(500),e2(jt),t3(jt),ee(jt),x(6*jt),f1(jt)
      dimension ifix1(jp),t1(jt),t0(jt),mah(jt),f3(jt)
      character fig*1,fih*1,fii*1,ff1*7,ff2*8,ff0*7,fij*1,fil*1,fit*1
     *,fra*1,ff3*7,ff4*7,fol*1

c----Give initial value for initial similarity for the current trace----c
c----It can be used for a key value to carry out the GLI in time to ----c
c----calculate the reflection coefficient sequence when the initial ----c
c----similarity is lower than this value, when it is set to do so. ----c

      cpre=0.8

c---------ppc.dat is a data file for all input parameter--------------c

      open(4,file='ppd.dat',status='old')

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c  ff0:seismic trace file; nl:trace length; am0:first trace No. to invert    c
c                                                                            c
c aml :inteval trace No.; am2:last trace No. to invert; amw: Trace No.       c
c                                                                            c
c of the starting borehole; alm:No. of known layers; fil: if 'y' fix the    c
c                                                                            c
c extracted wavelet and invert for boundary locations before the wavelet    c
c                                                                            c
c is redifined by fitting and optimised by GLI inversion;                    c
c                                                                            c
c ff4: filename of logging data in the function of two way travel time       c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              read(4,76)ff0,nl,am0,am1,am2,amw,alm,fil,ff4
76            format(a7,1x,6i5,a1,1x,a7)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c  ff1:result file; ff2:result file for looking; ff3:intermediate results    c
c                                                                            c
c- ea,em:max. and min. acoutic impedance values for country rocks  -c
c                                                                            c
c-- ga: max. value for the acoustic impedance gradients; mtg: No. of --c
c                                                                            c
c--    iterations; jm:No. of samples in the well logging data file;    --c
c                                                                            c
c-- wisi,wipi:two determined weighting coefficients for initial guess  -c
c                                                                            c
c--       wisi + wipi should be equal to 1.                      --c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              read(4,78)ff1,ff2,ff3,ea,em,ga,mtg,jm,lp,wisi,wipi
78            format(a7,1x,a8,1x,a7,1x,3f6.2,3i4,2f4.2)

ccccc Following parameters used for inversing iterations  ccccc

              read(4,79)fif,ig0,mfl,mf2,almda01
              read(4,*)(ifix1(i),i=mfl,mf2)
              read(4,79)fig,ig1,mg1,mg2,almda00
              read(4,79)fm,in1,mn1,mn2,almda11
              read(4,*)(ifix(i),i=mn1,mn2)
              read(4,79)fih,ih1,mh1,mh2,almda22
              read(4,*)(ifix(i),i=mh1,mh2)
              read(4,79)fti,iil,mil,mi2,almda33
              read(4,*)(ifix(i),i=mil,mi2)
              read(4,79)fij,ij1,mj1,mj2,almda44
              read(4,*)(ifix(i),i=mj1,mj2)
79            format(a1,1x,3i4,f12.10)
              read(4,*)(mah(j),j=1,alm)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccc dt:sample rate (seconds); lt:length of trace; iwk:length of wavelet  c
cccc an:no. of layers of guess; iqq:searching range; mm:No. of layers of  c
cccc inversion; lk:time shift range; itj:test parameter for time shift.   c
cccc if akp=-1 then keep the amplitude spectrum of the wavelet fixed       c
cccc during the inversion otherwise, let akp=0                              c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
```

```
              read(4,*)dt,lt,iwk,an,iqq,mm,lk,itj,akp

ccc calculating range of inversing parameters  ccc

      open(3,file=ff2,err=99,iostat=ios)
              if(fil.eq.'y')fol='y'

              nm=nm0
              mgg=mg2-mg1
              almda0=almda00
              almda1=almda11
              almda2=almda22
              almda3=almda33
              almda4=almda44

              write(*,*)'this is ince program '
              open(2,file=ff1,access='direct',recl=4*lt)
              itg=0
              ntg=0
itee=0
              itef=0
              itg1=0
              itg2=0
              itg3=0
              itg4=0
              mg0=mg1
              maa=ma2-ma1
              mhh=mh2-mh1
              mii=mi2-mi1
              mjj=mj2-mj1+1
              mmm=mm
              ivww=lt
              iq=iwk/2
              lt1=lt-iwk+1
              lt2=3*alm+lp
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c     For next observed trace inversion and continuous inversion     c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      if(nm.eq.amw)goto 122

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c    Note:every time nm should equal to the value  last time    c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

111           continue
              almda0=almda00
              almda1=almda11
              almda2=almda22
              almda3=almda33
              almda4=almda44
              maa=ma2-ma1
              mhh=mh2-mh1
              mii=mi2-mil
              mjj=mj2-mjl+1
              mmm=mm
              ivww=lt
              iq=iwk/2
              lt1=lt-iwk+1
              lt2=3*alm+lp
              open(5,file=ff0,access='direct',recl=4*nl,status='old')
              read(5,rec=nm)(e1(j),j=1,lt+lk)
              close(5)
              open(4,file=ff3,status='old')
              read(4,*)jif,lpa,ama,ity,tt0,older
              read(4,*)(r0(k),k=1,mm)
      read(4,*)(t2(k),k=1,mm)
      read(4,*)(e3(k),k=1,mm)
      read(4,*)(g1(k),k=1,mm)
              read(4,*)(pf2(k),k=1,lp)
              read(4,*)(w(k),k=1,ivww)
              read(4,*)(f(k),k=1,iwk)
              close(4)
              do 106 i=1,mm
              r3(i)=t2(i)/dt
              r3(i+mm)=e3(i)
              r3(i+2*mm)=g1(1)
106           continue
              do 107 k=1,lp
107           r3(k+3*mm)=pf2(k)
              do 108 j=1,ivww
108           w3(j)=w(j)
              do 109 j=1,iwk
109           f3(j)=f(j)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c  Constructing the interpretive information for initial guess for    c
c  boundary locations.                                               c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              if(nm.le.119)then
              if(am1.eq.1) then
              gmt=(40-am)*(30./80.)
              if(nm.eq.119)tt0=gmt
              else
              gmt=(119-am)*(30./80.)+tt0
              end if
              else if(nm.ge.120.and.nm.le.199)then
              if(am1.eq.1)then
              gmt=(120-am)*(15./80.)+tt0
              if(nm.eq.199)tt0=gmt
              else
              gmt=(199-am)*(15./80.)+tt0
              if(nm.eq.120)tt0=gmt
              end if
              else if(nm.ge.200)then
              if(am1.eq.1) then
              gmt=(200-am)*(5./80.)+tt0
              else
              gmt=(279-am)*(5./80.)
              if(nm.eq.200)tt0=gmt
              end if
              end if
              mg1=mg0+int(gmt)
              mg2=mg1+mgg
```

```
              write(*,*)'No. of trace:',am,' ranges of window:',mg1,mg2

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c   Constructing the initial guess model using both information   c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              do 117 i=1,mm
              if(i.lt.mm)t2(i)=wisi*(t0(i)+gmt*dt)+wipi*t2(i)
              rr(i)=t2(i)/dt
              rr(i+mm)=e3(i)
117           rr(i+2*mm)=g1(i)
           do 116 k=1,lp
116           rr(3*mm+k)=pf2(k)
              lt2=3*mm+lp

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c         subroutine wtg used for generating acoustic impedance       c
c         sequence by input boundaries, acoustic impedance values     c
c         at the boundaries and their gradients.                      c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              call wtg(rr,lt2,ee,lt,lp)

              do 118 i=1,lt
              e(i)=ee(i)
118           e2(i)=0.
              do 113 i=1,mg1-1
113           e1(i)=0.
              do 114 i=mg2+1,lt
114           e1(i)=0.

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c         Normalise the observed trace by total energy         c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              ana=0.
              do 754 i=mg1,mg2
              ana=e1(i)**2+ana
754           continue
              cc=sqrt(ama/ana)
              ana=0.
              do 756 i=mg1,mg2
              e1(i)=e1(i)*cc
              ana=e1(i)**2+ana
756           continue

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      Subroutine tgw used for generating a reflection coefficient  c
c      sequence by the same input data as subroutine wtg           c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              call tgw(rr,lt2,r,lt,lp)

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      Subroutine waf is used for produce a wavelet in frequency   c
c      domain by 7 or 8 parameters. Subroutine wat is to truncate  c
c      the wavelet into the the length of the wavelet in the time  c
c      domain for watching on the screen or on the printer.        c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              if(ff.eq.'y') then
              call waf(w,lt,pf2,dt,lp,0,ity,a,akp)
              call wat(w,lt,f1,dt,iwk)
              do 758 j=1,iwk
              jl=j
758           f(j)=f1(j1)
              end if

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      FFF is a subroutine to calculate the forward-trace in time   c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)
              ants=0.
              aqq=0.
              do 755 i=mg1,mg2
              aqq=(e2(i))**2+aqq
              ants=e1(i)*e2(i)+ants
755           continue
              cc=sqrt(ants**2/(ans*aqq))
              write(3,*)'Guess Correlate Coefficient==',cc
c             cpre=cc
              nn=mm
              itg=0
              ntg=0
         itee=0
              itef=0
              itg1=0
              itg2=0
              itg3=0
              itg4=0
              itit=1
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      When the inversed trace is the first trace near the well   c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
122           continue
              pp4=0.
              if(am.eq.amw)then
              if(ff0.eq.'result0')then

ccccccccccccccccccc   Synthetic Case   ccccccccccccccccc

              open(9,file=ff0,status='old')
              read(9,*)ijf,lpn
              read(9,*)(t3(k),k=1,nlm)
              read(9,*)(e3(k),k=1,nlm)
              read(9,*)(g1(k),k=1,nlm)
              read(9,*)(pf1(k),k=1,lp)
              close(9)
              call waf(w,lt,pf1,dt,lp,pp4,ity,a,0)
              call wat(w,lt,f1,dt,iwk)
              write(2,rec=1)(f1(j),j=1,lt)
              do 730 j=1,iwk
c             jl=lt/-iwk/2+j
              jl=j
              f(j)=f1(j1)
730           continue
           do 731 k=1,nlm
              rr(k)=t3(k)/dt
              rr(k+2*nlm)=g1(k)
              rr(k+nlm)=e3(k)
```

```
731           continue
           do 706 k=1,lp
706           rr(3*mlm+k)=pf1(k)
              call tgw(rr,lt2,r,lt,lp)
              call fff(w,lt,r,e1,lt,mg1,mg2,iq,ity)
              ama=0.
              do 735 j=1,lt
              ama=e1(j)*e1(j)+ama
735           continue
              call wtg(rr,lt2,e,lt,lp)
c             write(2,rec=5)(e(k),k=1,lt)
              else

ccccccccccccccccccccccccccc   Field Case   cccccccccccccccccccccccc

              open(5,file=ff0,access='direct',recl=4*nl,status='old')

ccccccc          input data file by direct file mode        cccccccccc

              read(5,rec=am)(e1(k),k=1,lt)
              write(*,*)'number of trace is:',nm
              close(5)
              do 918 i=1,lt
              if((i+itj).le.0.or.(i+itj).gt.lt) goto 918
              e2(i+itj)=e1(i)
918           continue
              do 919 i=1,lt
919           e1(i)=e2(i)
              do 727 i=1,mg1-lk
727           e1(i)=0.
              do 728 i=mg2+lk,lt
728           e1(i)=0.

cccc          Normalize the trace with its average energy        cccc

              amax=0.
              do 723 i=1,lt
              amax=e1(i)*e1(i)+amax
723           continue
              eamax=amax/(mg2+lk-(mg1-lk)+1)
              ca=sqrt(eamax/amax)
              do 724 j=1,lt
              e1(i)=e1(i)*ca
724           continue
              ama=0.
              do 725 j=1,lt
              ama=e1(j)*e1(j)+ama
725           continue

cccccccccccccccccccccccccccccccccccccccccccccccccccc
c         read well logging data   c
cccccccccccccccccccccccccccccccccccccccccccccccccccc

              open(8,file=ff4,status='old')
              do 721 k=1,jm
              read(8,93)x(k),x(k+jm),x(k+2*jm),x(k+3*jm),x(k+4*jm),x(k+5*jm)
721           continue
93            format(6f11.3)
              close(8).
              do 726 i=1,mg1-1
              e(i)=x(mg1+2*jm)*x(mg1+3*jm)/1000.
726           continue
              do 729 i=mg2+1,lt
              e(i)=x(mg2+2*jm)*x(mg2+3*jm)/1000.
729           continue
cccccccccccc   if mg2 less than jm,otherwise it should be different   cccccccccccccc
              do 722 k=mg1,mg2
              e(k)=(x(k+2*jm)*x(k+3*jm))/1000.
722           continue
              write(2,rec=6)(e(i),i=1,lt)
              end if

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccc    read initial guess for the inverse model      cccc
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              read(4,*)(t2(k),k=1,nn)
              read(4,*)(e3(k),k=1,nn)
              read(4,*)(g1(k),k=1,nn)
              read(4,*)(pf2(k),k=1,lp)
              pff1=pf2(3)
              pff2=pf2(4)
              pff3=pf2(5)
              pff4=pf2(6)
              if(ff.eq.'y') then
              do 666 k=1,lp
666           pf1(k)=pf2(k)
              end if
              call waf(w,lt,pf2,dt,lp,pp4,ity,a,0)
              call wat(w,lt,f1,dt,iwk)
              mg0=mg1
              close(4)
              end if
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c         get the real reflected coefficients    c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              if(ff0.ne.'result0')then
              r(1)=0.
              do 712 j=2,lt
              r(j)=(e(j)-e(j-1))/(e(j)+e(j-1))
712           continue
              else
              call tgw(rr,lt2,r,lt,lp)
              end if
c
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c--Using Winner Shaping Filter to extract wavlet,calculate time shift--c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              if(am.eq.amw)then
              mp1=mg1-lk
              mp2=mg2+lk
         acc=0.
              do 404 i=1,2*lk+1
              jj=(i-lk-1)
              do 409 j=1,lt
409           e0(j)=0.
              do 443 j=1,lt
              k=j+jj
```

```fortran
        if(k.le.0.or.k.gt.lt) goto 443
        e0(k)=e1(j)
443   continue

cccccccc        Solving the normal equation     ccccccccc

      call extl1(r,mg1,mg2,e0,mg1,mg2+iwk,f,1,iwk)

cccc  Tranfer the wavelet to the frequency domain and   ccccc
cccc  compute the forward-modelled trace by convolution model  ccc

      do 810 j=1,lt
         if(j.le.iwk)then
         w(j)=cmplx(f(j))
         else
         w(j)=(0.,0.)
         end if
810   continue
      ity=0
      call fft(w,lt,0)
      call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)

cccc        Calculate the error energy between the forward-modelled  ccc
cccc        trace and the observed trace, work out the time shift.  cccc

      anee(i)=0.
         aqq=0.
         ama=0.
      do 442 j=mg1,mg2
         aqq=aqq+e2(j)**2
         ama=ama+e0(j)**2
      anee(i)=anee(i)+(e0(j)-e2(j))**2
442   continue
      anee(i)=anee(i)/ama*100
      amin=10000.
      do 441 i=1,2*lk+1
      if(anee(i).lt.amin)then
       amin=anee(i)
       imin=i
      end if
441   continue
      write(*,*)'imin==',imin-lk-1
         lpa=imin-lk-1

      do 448 j=1,lt
      e2(j)=0.
448   continue
      do 449 j=1,lt
      f(j)=0.
      jj=j+lpa
      if(jj.lt.0.or.jj.gt.lt) goto 449
      e2(j)=r(jj)
449   continue
      do 455 j=1,mg1-1
455   e2(j)=0.
      do 456 j=mg2+1,lt
456   e2(j)=0.
      do 447 j=mg1,mg2+iwk
447   r(j)=e2(j)
      call extl1(r,mg1,mg2,e1,mg1,mg2+iwk,f,1,iwk)

cccc        Write out the extracted wavelet on the file    cccc

      write(2,rec=1)(f(j),j=1,iwk)
      do 811 j=1,lt
      if(j.le.iwk) then
      w(j)=cmplx(f(j))
      else
      w(j)=(0.,0.)
      end if
811   continue
      ity=0
      call fft(w,lt,0)
      call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)
      write(2,rec=9)(e2(j),j=1,lt)
      write(*,*)'This wavelet extracted by Winner Shaping Filter'
      aats=0.
      ama=0.
      anta=0.
      aqq=0.

ccccc        Calculate the SNR of the observed trace   ccccc

      do 414 i=mg1,mg2
      ama=ama+e1(i)**2
      aqq=aqq+e2(i)**2
      anta=e1(i)*e2(i)+anta
      anta=(e2(i)-e1(i))**2+anta
414   continue
      cc=sqrt(anta**2/(ama*aqq))
      write(*,*)'Best initial N/S Ratio',anta/aqq
      anta=(anta/ama)*100.
      write(*,*)'Best Correlate Coefficient==',cc
      write(*,*)'Energy of Observed,forward,Error:',ama,aqq,anta
      end if

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
ccccccccccccc    Prepare to inverse data in two steps    ccccccccccc
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

ccccc First step(iii=1) is to locate the positions of desired layers ccccc
c Either in frequency domain or time domain depending on ftl or ftg  c

791      lt2=3*an+lp
         iii=2
         if(am.ne.amw) goto 1111
         e00=e3(1)
      do 450 k=1,an
         if(k.lt.an) then
         r1(k)=t2(k)/dt-lpn
         t0(k)=r1(k)*dt
         end if
         r1(k+2*an)=g1(k)
450      r1(k+an)=e3(k)
         r1(an)=t2(an)/dt
         t0(an)=t2(an)
      do 436 k=1,lp
436      r1(3*an+k)=pf2(k)
         do 457 k=1,3*an+lp
457      rr(k)=r1(k)
      call wtg(r1,lt2,ee,lt,lp)
```

```fortran
         aats=0.
         antt=0.
      do 535 i=mg1,mg2
         aats=(ee(i)-e(i))**2+aats
         antt=(e(i))**2+antt
535   continue
      write(3,*)'initial RMS impedance error:',sqrt(aats/antt)
      write(*,*)'initial RMS impedance error:',sqrt(aats/antt)
      if(am.eq.amw)write(2,rec=5)(ee(i),i=1,lt)
      if(ftg.eq.'a')mm=an
99    if(ios.ne.0)write(*,*)'error=======',ios
      call tgw(r1,lt2,r,lt,lp)
         call fff(w,lt,r,e0,lt,mg1,mg2,iq,ity)
         j2=j2+1
1111     lt1=lt-iwk+1
         dg=0.001
         ds=0.01
         dad=.001
         ddd=1.0
         de=0.001
         df=1./(lt*dt)
         dp=.01
         ite1=0
         izq=0

cc The first step(iii=1) is to inverse boudaries in time using GLI

      izq=0
         if(ftg.eq.'y'.and.am.ne.amw.and.cpre.lt.0.75)then
ggg=0.
         iii=1
      goto 989
      end if

c This step(iii=2) is to inverse boundaries using GLI but fix the wavelet c
         if(ftl.eq.'y'.and.am.eq.amw)then
ggg=1.
         iii=2
         goto 989
         end if

1000  continue
         itee=0
      if(am.ne.amw) goto 988

ccc The 2nd step(iii=2) is to inverse wavelet using GLI in frequency ccc

      call tgw(r1,lt2,r,lt,lp)

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c    Subroutine apw is to fit the wavelet defined by 7 or 8 parameters  c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

         if(ftj.eq.'y'.or.(ftf.eq.'y'.and.am.eq.amw))then
         call apw(dt,lt,iwk,f,pf2,lp,a,akp)
         call waf(w,lt,pf2,dt,lp,0.,ity,a,akp)
         call wat(w,lt,f1,dt,iwk)
      do 397 k=1,lp
397      r1(3*an+k)=pf2(k)
         write(2,rec=2)(f1(j),j=1,lt)
         do 390 j=1,iwk
         j1=j
         f(j)=f1(j1)
390      continue
         end if
         call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)
         aats=0.
         ama=0.
         anta=0.
         aqq=0.
      do 313 i=mg1,mg2
         ama=(e1(i))**2+ama
         aqq=(e2(i))**2+aqq
         anta=e1(i)*e2(i)+anta
         anta=(e2(i)-e1(i))**2+anta
313      continue
         write(*,*)'Best initial N/S Ratio',anta/aqq
         cc=sqrt(anta**2/(ama*aqq))
         anta=(anta/ama)*100
         write(*,*)'Best Correlate Coefficient==',cc
         write(*,*)'Energy of Observed,forward and Error:',ama,aqq,anta
988      continue
         if(ftl.eq.'y'.and.am.eq.amw)then
ggg=-1.
         else if(ftn.eq.'y') then
ggg=1.
         else if(fth.eq.'y') then
ggg=2.
         else if(fti.eq.'y') then
ggg=3.
         else if(ftg.eq.'y') then
ggg=4.
         end if
         iit=1
         lt1=lt
989      continue
400      if(iii.eq.1)ll=an
      if(iii.ge.2)ll=mm
      if(ftg.eq.'a'.and.iii.ge.2)ll=an
         lt2=3*ll+lp
         iit=1
         if(iii.eq.2)call tgw(r1,lt2,r,lt,lp)
         if(iii.ge.2) then
         ll=lt2
         if(ftl.eq.'y'.and.am.eq.amw.or.am.ne.amw)then
         if(izq.eq.0)then
         do 445 i=1,lt2
445      r1(i)=rr(i)
         end if
         end if
         else
         ll=lt
         do 446 i=1,lt
446      r1(i)=0.
         end if

ccccc Set an initial error value as large as possible ccccc

         emax=1000.

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
```

110

```fortran
210        if(atg.ge.mtg)goto 211

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
ccc For each different iterations,to set different iterative parameters c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

212   if(ftg.eq.'y'.and.ggg.eq.0.and.iii.eq.1)then
               itg=ig1
               almda=almda0
        ma1=mg1
                ma2=mg2
           else if(ftl.eq.'y'.and.ggg.eq.1.and.nm.eq.nmw)then
                     itg=ia1
                     almda=almda1

               ma1=ma1
                 ma2=ma2
           else if(ftl.eq.'y'.and.ggg.eq.-1.and.nm.eq.nmw) then
               itg=ig0
               almda=almda01
               ma1=mf1
               ma2=mf2
               ftf='b'
        else if(ftn.eq.'y'.and.ggg.eq.1.)then
               itg1=ia1
               itg=itg+itg1
               if(izq.1.and.izp.eq.1)almda1=almda1/100.
               almda=almda1
               ma1=ma1
               ma2=ma2
           else if(fth.eq.'y'.and.ggg.eq.2.)then
               itg2=ih1
         ma1=mh1
         ma2=mh2

               almda=almda2
           else if(fti.eq.'y'.and.ggg.eq.3.)then
               itg3=ii1
               itg=itg+itg3
                     ma1=mi1
                     ma2=mi2
               almda=almda3
           else if(ftj.eq.'y'.and.ggg.eq.4.)then
               itg4=ij1
               itg=itg+itg4
                     ma1=mj1
                     ma2=mj2
               almda=almda4
           end if
         j=0
               do 465 i=ma1,ma2
               if(ggg.ge.1.)then
               if(ifix(i).eq.i)goto 465
               else if(ggg.eq.-1.) then
               if(ifix1(i).eq.i)goto 465
               end if
           j=j+1
           lista(j)=i
465              continue
                 ma=j
500   iter=itee
                 itee=itg
600   iter=iter+1
          if(iter.eq.1.or.iter.eq.1+itef)aa=-1.

cc Decide to apply a initial inversion (if itef=itg means apply it   cc
c before every step,itef=0 means apply it only before the first step) c
cc mqw is a subroutine to carry out the inversion by GLI method cc

               itef=itg
c      itef=0


               if(ggg.eq.0.and.iii.eq.1)then

ccccccc  This is the first inversion step used to obtain the   ccccc
cccc reflection coefficient sequence in time domain by GLI cccc

               do 747 i=1,lt
               if(i.le.lt1)then
               r1(i)=0.0
               else
               i1=i-lt1
               r1(i)=f(i1)
               end if
747            continue
               do 746 j=1,iwk
746            w2(j)=cmplx(f(j))
               if(iter.eq.1)bb=emax
       call mqw(e1,lt,r1,l1,lista,ma,cover,alpha,ma,er,aa,bb,akp
      * ,cc,dt,ggg,w2,iwk,iww,ama,mg1,mg2,mah,almda,iq,ity,y1,y1)
               else

cccc  This is the second inversion step for normally use   ccccc

               if(iter.eq.1)bb=emax
               l1=lt2
       call mqw(e1,lt,r1,l1,lista,ma,cover,alpha,ma,er,aa,bb,akp
      * ,cc,dt,ggg,w,iwk,iww,ama,mg1,mg2,mah,almda,iq,ity,a,ee)
               almda=aa

cccccccc if use similarity as a criterio other than error,then
cccccccc lt change to gt and emax to emin .

               error(itit)=bb
           end if
               if(aa.eq.0.) goto 520
           if(ggg.eq.0.)then
               if(iter.lt.itg)goto 600
               goto 555
           end if
502         continue
            if(error(itit).lt.emax)emax=error(itit)
            itit=itit+1
            if(iter.ge.itg) then
                     if(ftl.eq.'y'.or.ftf.eq.'y') then
                     if(am.eq.amw) then
                     itg=0
                     iter=0
                     end if
```

```fortran
               end if
               goto 504
               else
        goto 600
               end if
555         continue
            if(ftg.eq.'y'.and.ggg.eq.0.)then

cccc Automatically picking up the preset No. of layers due to cccc
ccccc the relative large amplitudes in the spiked trace ccccccc

               do 172 i=1,ma1-1
               r2(i)=0
172            r1(i)=0.
               do 173 i=ma2,lt
               r2(i)=0.
173            r1(i)=0.
               amax=0.
               rmax1=0.
               do 157 i=ma1,ma2
               r2(i)=0.
               r4(i)=r1(i)
157            continue
               iqq1=iqq
153            k=0
            do 155 i=ma1,ma2
               max=1
               do 154 j=i-iqq1,i+iqq1
               if(j.eq.i)goto 154
               if(abs(r4(i)).gt.abs(r1(j)))then
               if(max.ne.0)max=-1
               else
               max=0
               end if
154            continue
               if(max.eq.-1)then
               k=k+1
               nol(k)=i
               endif
155         continue
            if(k.lt.mmm) then
               iqq1=iqq1-1
               goto 153
            end if
            write(*,*)'no. of layers(calculate and preset)',k,mmm
90    do 91 j=1,mm-1
      amax=0.
      do 92 i=1,k
      ampr=abs(r4(nol(i)))
      if(ampr.gt.amax)then
      amax=ampr
      tty=nol(i)*dt
      iti(j)=i
      end if
92    continue
      r4(nol(iti(j)))=0.
      t3(j)=tty
91    continue
      do 98 i=mm-1,1,-1
      amax=0.
      do 97 j=1,mm-1
      if(t3(j).gt.amax)then
      amax=t3(j)
      j1=j
      end if
97    continue
      t3(j1)=0.
      t1(i)=amax
98    continue
      amed=4*dt
      do 933 i=1,mm-1
      amint=t1(i)-t2(i)
      ilx=0
      if(abs(amint).gt.amed.and.amint.lt.0)then
      do 934 j=1,k
      if(ilx.eq.1) goto 934
      if(abs(nol(j)*dt-t2(i)).le.amed)then
      t1(i)=nol(j)*dt
      ilx=1
      end if
934   continue
      else if(abs(amint).gt.amed.and.amint.gt.0) then
      do 299 j=k,1,-1
      if(ilx.eq.1) goto 299
      if(abs(nol(j)*dt-t2(i)).le.amed)then
      t1(i)=nol(j)*dt
      ilx=1
      end if
299   continue
      end if
933   continue
      do 935 i=1,mm-1
935   t2(i)=t1(i)
      do 511 i=1,mm
      r1(i)=t2(i)/dt
               r1(i+2*mm)=g1(i)
               if(i.gt.nn)e3(i)=e3(nn)
511   r1(i+mm)=e3(i)
      do 512 i=1,lp
512   r1(3*mm+i)=pf2(i)
      write(*,*)(r1(i),i=1,mm)
      write(3,*)'ERR',er,' SIMI',cc,' TRA',am,' RAN.',mg1,mg2
      write(3,*)' guess location     inversion location'
      do 517 i=1,mm
      if(i.gt.nn)then
      write(3,103)i,r1(i)*dt,r1(i+mm),r1(i+2*mm)
      else
      write(3,101)i,rr(i)*dt,rr(i+ll),rr(i+2*ll),r1(i)*dt,
     * r1(i+mm),r1(i+2*mm)
      end if
517   continue
      do 518 i=1,lp
518   write(3,102)i+ll*3,rr(i+ll*3),r1(i+mm*3)
               iii=2
               izq=1
               if(ftl.eq.'y')call waf(w,lt,pf2,dt,lp,pp4,ity,a,akp)
               do 208 i=1,lt2
208            rr(i)=r1(i)
               goto 1000
               endif
               do 209 i=1,lt2
```

```
209        rr(i)=r1(i)
504   continue

cccc Save the individual damping factors for each iteration cccc

                  if(ggg.eq.-1.)almda01=aa
           if(ggg.eq.1.)almda1=aa
           if(ggg.eq.2.)almda2=aa
           if(ggg.eq.3.)almda3=aa
                  if(ggg.eq.4.)almda4=aa
                  if(fti.eq.'y'.and.am.eq.amw)then
                         ggg=-1
                         ma1=mf1
                         ma2=mf2
                  fti='n'
                         goto 1000
                  end if
                  if(fth.eq.'y'.and.ggg.lt.1.)then
                         ggg=1.
                         ma1=ma1
                         ma2=ma2
                         goto 212
                  end if
                  if(fth.eq.'y'.and.ggg.lt.2.)then
                         fth='n'
                         ggg=2.
                         ma1=mh1
                         ma2=mh2
                         goto 212
                  end if
           if(fti.eq.'y'.and.ggg.lt.3.)then
                         fti='n'
                         ggg=3.
                         ma1=mi1
                         ma2=mi2
                         goto 212
                  end if
                  if(ftj.eq.'y'.and.ggg.lt.4.)then
                         ftj='n'
                         ggg=4.
                         ma1=mj1
                         ma2=mj2
                         goto 212
                  end if

cccc        Work out for next kind of parameter to inverse    cccc

                  if(fth.eq.'y')then
                  ggg=1.
                  goto 233
                  end if
                  if(fth.eq.'y')then
                  ggg=2.
                  goto 233
                  else if(fti.eq.'y')then
                  ggg=3.
                  goto 233
                  else if(ftj.eq.'y') then
                  ggg=4.
                  end if
233   ntg=ntg+1

                  if(er.le.2.0) goto 520
                  goto 210
520   write(*,*)'error is less than expected'
                  goto 530
211          write(3,*)'iterative time reached preset value'

cc Write the inverse result,some of them for next trace inversion cc

530          continue
           write(3,*)'ERR',er,' SIMI',cc,' TRA',am,' RANGE',mg1,mg2
           write(3,*)' guess location and impedance   inversion results'
                  do 199 i=1,ll
           write(3,101)i,rr(i)*dt,rr(i+ll),rr(i+2*ll),r1(i)*dt,r1(i+ll),
     *     r1(i+2*ll)
199   continue
                  do 198 i=1,lp
198          write(3,102)i,rr(i+3*ll),r1(i+3*ll)
101          format(1x,i4,2x,f9.5,2x,f9.5,2x,f9.5,2x,f9.5,2x,f9.5,2x,f9.5)
102          format(1x,i4,2x,f10.5,2x,f10.5)
103                  format(1x,i4,35x,f9.5,2x,f9.5,2x,f9.5)
                  ll2=3*mm+lp
                  if(ftj.eq.'y'.or.fol.eq.'y')then
                  do 526 i=1,lp
526          pf2(i)=r1(3*mm+i)
                  call waf(w,ll,pf2,dt,lp,0.,ity,s,akp)
                  call waf(w,ll,f1,dt,iwk)
                  do 527 i=1,iwk
c          i1=i+ll/2-iwk/2
                  i1=i
                  f(i)=f1(i1)
527          continue
                  write(2,rec=3)(f(j),j=1,iwk)
                  end if
                  open(4,file=ff3,status='old')
                  write(4,*)am,lpu,ama,ity,t0,er
                  write(4,*)(t0(j),j=1,mm)
                  write(4,*)(r1(j)*dt,j=1,mm)
                  write(*,*)(r1(j)*dt,j=1,mm)
                  write(4,*)(r1(j),j=mm+1,2*mm)
                  write(4,*)(r1(j),j=2*mm+1,3*mm)
                  write(4,*)(r1(j),j=3*mm+1,3*mm+lp)
                  write(4,*)(w(j),j=1,lt)
                  write(4,*)(f(j),j=1,iwk)
                  close(4)
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                       OUTPUT RESULTS                         c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                  call tgw(r1,lf2,r,lt,lp)
                  call fff(w,lt,r,e0,lt,mg1,mg2,iq,ity)
                  if(am.eq.amw)write(2,rec=10)(e1(i),i=1,lt)
                  if(am.eq.amw)write(2,rec=11)(e0(i),i=1,lt)

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c          arrange the things to display and normalize them         c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                  call wtg(r1,lf2,r,lt,lp)
                  write(2,rec=7)(r(j),j=1,lt)
```

```
                  if(am.ge.amw)ijf=(am-amw)/abs(am1)+12
                  if(nm.le.amw)ijf=(amw-nm)/abs(am1)+12
                  arr1=0.
                  do 798 i=1,iwk
                  if(abs(f(i)).gt.arr1)arr1=abs(f(i))
798          continue
                  arr0=0
                  arr2=0.
                  do 930 j=mg1,mg2
                  if(abs(ee(j)).gt.arr2) arr2=abs(ee(j))
930          continue
                  do 931 j=1,lt
                  r4(j)=0.
                  e0(j)=0.
931          continue
                  do 94 j=mg1-50,mg2+30
                  r4(j)=r(j)
                  if(abs(r4(j)).gt.arr0)arr0=abs(r4(j))
94           continue
                  do 941 j=mg1-200,mg2-200
                  r4(j)=arr0*(ee(j+200)/arr2)
941          continue
                  do 799 i=1,iwk
799          f(i)=arr0*(f(i)/arr1)
                  do 95 j=lt,lt-er/2,-1
                  r4(j)=arr0
95           continue
                  write(2,rec=ijf)(f(i),i=1,iwk),(r4(i1),i1=iwk+1,lt)
                  write(3,*)(r4(j),j=mg1,mg2),'maximum value==',arr0
974          nm=nm+am1
                  if(am.ne.am2+am1)goto 111

           close(2)
           stop
           end


**********************************************************************
**********************************************************************
**********************************************************************


           subroutine mqw(y,ndata,a,ma,lista,mfit,covar,alpha,nca,chisq,
     *alam,bb,ak,cc,dt,ggg,w,iwk,iww,ene,ma1,ma2,mah,ada1,iq,ity,s,ee)

c   This subroutine is to carry out GLI inversion scheme   c

           PARAMETER (TOL=1.E-5,aa=512)
                  complex w(iwk),w1(2048)
           common /wavelet/ddd,de,dg,dp,ds,df,dad,lp,ga,ea,em
           DIMENSION Y(NDATA),A(MA),ALPHA(NCA,NCA),da(aa),aaa(200),s(iww),
     *COVAR(NCA,NCA),LISTA(MA),ATRY(aa),BETA(aa),pf(lp),ee(ndata),
     *mah(ma),cri(3)
                         lma=1
                         do 123 i=1,iww
123          w1(i)=w(i)
           IF(ALAM.LT.0.)THEN
                         do 132 i=1,3
132          cri(i)=0.
           KK=MFIT+1
           DO 12 J=1,MA
           IHIT=0
           DO 11 K=1,MFIT
           IF(LISTA(K).EQ.J)IHIT=IHIT+1
11           CONTINUE
           IF (IHIT.EQ.0) THEN
           LISTA(KK)=J
           KK=KK+1
           ELSE IF (IHIT.GT.1) THEN
           PAUSE 'Improper permutation in LISTA '
           ENDIF
12           CONTINUE
           IF (KK.NE.(MA+1)) PAUSE 'Improper permutation in LISTA(kk>ma+1)'
                  lma=0
                  alam=ada1

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c   mrw is a subroutine to construct the GLI equations for solving   c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                  call mrw(y,ndata,a,ma,lista,mfit,alpha,beta,nca,chisq,dt,
     *  ggg,iwk,iww,ene,ma1,ma2,bb,cc,w1,iq,lma,ity,s,ee,ak)

                         bb=chisq
                         cri(1)=chisq
                  DO 13 J=1,MA
                  ATRY(J)=A(J)
13           CONTINUE
           END IF
                         ikj=0
555          continue
                  DO 15 J=1,MFIT
                  DO 14 K=1,MFIT
                  COVAR(J,K)=ALPHA(J,K)
14           CONTINUE
                  COVAR(J,J)=ALPHA(J,J)+alam
                  DA(J)=BETA(J)
15           CONTINUE

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cc   gau is a subroutine to obtain the solutions of equations    cc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

666   call gau(covar,mfit,nca,da,1,1,ijk)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c  if SVD was found, try to increase the dapming coefficient   c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

           if(ijk.eq.1)then
                         ikj=ikj+1
           alam=alam*10.
                         if(ikj.lt.10) then
                         ijk=0
                  goto 555
                  else
                         pause
                         end if
                  endif
124   continue
                  ochisq=chisq
```

```
                 amax=0.
                 mb1=ma-lp
                 mb2=(ma-lp)/3
                 emax=0.
        DO 16 J=1,MFIT
        ll=lista(j)

        aaa(j)=a(ll)+da(j)

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c           make sure the constraints are satisfied        c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

        if(ggg.ge.1.and.ggg.lt.4.)then
         if(ll.le.mb1-mb2.and.aaa(j).lt.0.)aaa(j)=a(ll)
          if(ggg.eq.1)then
                       if(aaa(j).le.ma1)aaa(j)=ma1
                       if(aaa(j).ge.ma2)aaa(j)=ma2
          end if
                       if(ll.gt.mb2.and.ll.le.mb1-mb2)then

cc the acoustic impedances must be within the maximum and minimum cc

                  if(aaa(j).gt.ea.and.mod(ll,2).ne.0)aaa(j)=ea
                  if(aaa(j).lt.em.and.mod(ll,2).ne.0)aaa(j)=em
                  end if
                  if(ll.gt.mb1-mb2.and.ll.le.mb1)then
                    if(abs(aaa(j)).gt.ga)aaa(j)=a(ll)
                    end if
                  end if
                  if(ggg.eq.4.or.ggg.eq.-1.)then
                    if(ll.ge.mb1+3.and.ll.le.mb1+6)then
                    if(aaa(j).lt.0) aaa(j)=a(ll)
                    end if
                  end if
                  end if
        atry(ll)=aaa(j)

ccc The thicknesses of the coal seams must not be over set values ccc

                  if(mod(ll,2).eq.0.and.(atry(ll)-atry(ll-1)).gt.mah(ll))then
                  atry(ll)=atry(ll-1)+mah(ll)
                  end if

ccc The thicknesses of the country rocks must not be over set values ccc

                  if(mod(ll,2).ne.0.and.(atry(ll)-atry(ll-1)).gt.mah(ll))then
                  atry(ll)=atry(ll-1)+mah(ll)
                  end if
                  end if
                  if(ggg.eq.4.or.ggg.eq.-1.)then
                  if(ll.ge.mb1+4.and.ll.le.mb1+6)then

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c the gap between the two frequencies should bigger than 10 Hz. c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                  if(int(atry(ll))-int(atry(ll-1)).lt.10)then
                  atry(ll)=atry(ll-1)+10.
                  end if
                  end if
                  end if
                  aaa(j)=atry(ll)
16      CONTINUE
                  ww=1.

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c    secure the order of the boundaries are not reversed    c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                  if(ggg.eq.1.)then
                  do 26 j=mfit,1,-1
                  ll=lista(j)
                  amax=0.
                  do 27 k=1,mfit
                  if(aaa(k).gt.amax)then
                  amax=aaa(k)
                  ii=k
                  end if
27                continue
                  aaa(ii)=0.
                  atry(ll)=amax
26                continue
                  end if
                  if(ggg.eq.-1.or.ggg.eq.4.)then
                  do 88 i=1,lp
                  pf(i)=atry(mb1+i)
88                continue
                  call waf(w1,iww,pf,dt,lp,0.,ity,s,sk)
                  end if
                  lma=1
        CALL MRW(Y,NDATA,ATRY,MA,LISTA,MFIT,COVAR,DA,NCA,CHISQ,dt
        *,ggg,iwk,iww,ene,ma1,ma2,bb,cc,w1,iq,lma,ity,s,ee,sk)
                  cri(3)=chisq
                  IF(chisq.lt.bb)THEN

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cc the current inversion got improved, decrease the damp factor cc
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                  if(ggg.eq.4.or.ggg.eq.-1.)then
                  do 8 j=1,iww
8                 w(j)=w1(j)
                  end if
        alam=0.05*alam
                  cri(2)=chisq
        bb=chisq
        DO 18 J=1,MFIT
                  ll=lista(j)
        DO 17 K=1,MFIT
                  ALPHA(J,K)=COVAR(J,K)
17      CONTINUE
        BETA(J)=DA(J)
        A(ll)=ATRY(ll)
18      CONTINUE
        ELSE

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c          the current inversion is worse than previous one,     c
c          increase the damp factor and save the previous error  c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

29      alam=20.0*alam
```

```
              cri(1)=chisq
          chisq=bb
          endif
          return
          end
```

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```
        subroutine gau(a,n,np,b,m,mp,iii)

c   This subroutine is used for obtaining the solutions of the equations    c

        PARAMETER (NMAX=2048)
        real*4 a,b
        DIMENSION A(NP,NP),B(NP,MP),IPIV(NMAX),INDXR(NMAX),INDXC(NMAX)
        iii=0
        DO 11 J=1,N
         IPIV(J)=0
11      CONTINUE
        DO 22 I=1,N
         BIG=0.
         DO 13 J=1,N
          IF(IPIV(J).NE.1)THEN
            DO 12 K=1,N
             IF (IPIV(K).EQ.0) THEN
              IF (ABS(A(J,K)).GE.BIG)THEN
               BIG=ABS(A(J,K))
               IROW=J
               ICOL=K
              ENDIF
             ELSE IF (IPIV(K).GT.1) THEN
c            PAUSE 'Singular matrix (ipiv(k).gt.1)'
               iii=1
               return
             ENDIF
12          CONTINUE
          ENDIF
13       CONTINUE
         IPIV(ICOL)=IPIV(ICOL)+1
         IF (IROW.NE.ICOL) THEN
           DO 14 L=1,N
            DUM=A(IROW,L)
            A(IROW,L)=A(ICOL,L)
            A(ICOL,L)=DUM
14         CONTINUE
           DO 15 L=1,M
            DUM=B(IROW,L)
            B(IROW,L)=B(ICOL,L)
            B(ICOL,L)=DUM
15         CONTINUE
         ENDIF
         INDXR(I)=IROW
         INDXC(I)=ICOL
         IF (A(ICOL,ICOL).EQ.0.) then
           iii=1
           return
c          pause'Singular matrix(a(icol,icol)=0)'
         end if
         PIVINV=1./A(ICOL,ICOL)
         A(ICOL,ICOL)=1.
         DO 16 L=1,N
          A(ICOL,L)=A(ICOL,L)*PIVINV
16       CONTINUE
         DO 17 L=1,M
          B(ICOL,L)=B(ICOL,L)*PIVINV
17       CONTINUE
         DO 21 LL=1,N
          IF(LL.NE.ICOL)THEN
           DUM=A(LL,ICOL)
           A(LL,ICOL)=0.
           DO 18 L=1,N
            A(LL,L)=A(LL,L)-A(ICOL,L)*DUM
18         CONTINUE
           DO 19 L=1,M
            B(LL,L)=B(LL,L)-B(ICOL,L)*DUM
19         CONTINUE
          ENDIF
21       CONTINUE
22      CONTINUE
        DO 24 L=N,1,-1
         IF(INDXR(L).NE.INDXC(L))THEN
           DO 23 K=1,N
            DUM=A(K,INDXR(L))
            A(K,INDXR(L))=A(K,INDXC(L))
            A(K,INDXC(L))=DUM
23         CONTINUE
         ENDIF
24      CONTINUE
        RETURN
        END
```

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```
        SUBROUTINE MRW(Y,NDATA,A,MA,LISTA,MFIT,ALPHA,BETA,NALP,
        *CHISQ,dt,ggg,iwk,iww,ene,ma1,ma2,bb,ep,w1,iq,lma,ity,s,ee,sk)

c   This subroutine is used for constructing the linear equations for solving    c

        complex w1(iww)
        PARAMETER (nmax=4096)
        common /wavelet/ddd,de,dg,dp,ds,df,dad,lp,ga,ea,em
        DIMENSION Y(NDATA),ALPHA(NALP,NALP),BETA(MA),f(256),s(iww)
        * ,DYDA(nmax),LISTA(MFIT),A(MA),r(nmax),ee(ndata)
        dimension y1(nmax)
        DO 12 J=1,MFIT
        DO 11 K=1,J
        ALPHA(J,K)=0.
11      CONTINUE
```

113

```
      BETA(J)=0.
12    CONTINUE
      CHISQ=0.
      dy=0.
      wr=1.
      do 33 j=1,adata
33    y1(j)=0.
      if(ggg.eq.0.)then
      do 45 i=1,adata-iwk+1
45    r(i)=a(i)
      do 46 j=1,iwk
      jj=j+adata-iwk+1
46    f(j)=a(jj)
      do 844 j=1,adata
      if(j.le.iwk)then
      w1(j)=cmplx(f(j))
      else
      w1(j)=(0.,0.)
      end if
844   continue
      ity=0
      call fft(w1,adata,0)
      end if
      if(ggg.eq.0.) then
      call fff(w1,iwww,r,y1,adata,ma1,ma2,iq,ity)
      else
      call tgw(a,ma,r,adata,lp)
      call fff(w1,iwww,r,y1,adata,ma1,ma2,iq,ity)
      end if
      app=0.
      aqq=0.
      do 70 i=ma1,ma2
      app=y(i)*y1(i)+app
      aqq=(y1(i))**2+aqq
70    continue
      if(aqq.eq.0.)aqq=1.
      ep=sqrt(app**2/(ene*aqq))
      do 79 i=ma1,ma2
      dy=(y(i)-y1(i))**2+dy
79    continue
      chisq=(dy/ene)*100.
      if(chisq.lt.bb)then
      do 97 j=1,adata
      ee(j)=y(j)-y1(j)
97    continue
      end if
      if(lma.eq.1)then
      write(*,*)'both E. & errors,simi:',ene,aqq,bb,chisq,ep
      end if

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c  fu0 is used for calculate the coefficient of the Jacobian    c
c  matrix by using direct derivation to the model parameters    c
c  used in obtaining the reflection coefficient sequence        c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      DO 15 I=ma1,ma2
      if(ggg.eq.0.)then
      CALL FU0(i,r,DYDA,ma,adata,lista,mfit,f,iwk,adata-iwk+1)
      else

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c  fuw is used for calculate the jacobian matrix by finite      c
c  difference method, this need quite a long time to do it      c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      call fuw(i,a,dyda,ma,adata,y1(i),mfit,lista,iwk,iww,
     * dt,ma1,ma2,w1,iq,ity,a,ak)
      end if
      dy=y(i)-y1(i)
c     sig2i=1./(sig(i)*sig(i))
      sig2i=1.
      DO 14 J=1,MFIT
      WT=DYDA(LISTA(J))*SIG2I
      DO 13 K=1,J
      ALPHA(J,K)=ALPHA(J,K)+WT*DYDA(LISTA(K))
13    CONTINUE
      BETA(J)=BETA(J)+DY*WT
14    CONTINUE
c     CHISQ=CHISQ+DY*DY*SIG2I
15    CONTINUE
      DO 17 J=2,MFIT
      DO 16 K=1,J-1
      ALPHA(K,J)=ALPHA(J,K)
16    CONTINUE
17    CONTINUE
      RETURN
      END
```

```
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      subroutine fu0(ii,r,dyda,na,adata,lista,mfit,f,iwk,i2)
c  This subroutine is used for calculating the Jacobian coefficients by direct derivations  c
c  in the procedure for getting reflection oefficient sequence using OLI in time domain  c

      dimension r(na),dyda(na),lista(mfit),f(iwk)
      do 10 k=1,na
      dyda(k)=0.
10    continue
      do 11 j=lista(1),lista(mfit)
      if(j.gt.i2) then
      i4=(i2-j)+ii
      if(i4.lt.1) goto 11
      if(i4.gt.i2) goto 11
      dyda(j)=r(i4)
      else
      if(ii.le.na.and.ii-j.lt.0) goto 11
      i1=ii
      if(ii.gt.iwk)then
      i1=ii-iwk
      if(j-i1.le.0) goto 11
      dyda(j)=f(iwk+1-j+i1)
      else
      if(i1-j.lt.0) goto 11
      dyda(j)=f(i1-j+1)
      end if
      end if
```

```
11    continue
      return
      end

•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
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      subroutine fuw(ii,r,dyda,na,adata,yii,mfit,lista,iwk,iww
     * ,dt,ma1,ma2,w1,iq,ity,a,ak)

c  This subroutine is used for calculating the Jacobian coefficients by finite difference  c

      complex w(2048),w1(iww)
      parameter(amax=2048,idt=10,mn=512)
      common /wavelet/ddd,de,dg,dp,ds,df,dad,lp,ga,es,em
      dimension dyda(na),lista(mfit),pf(10),e(iww)
      dimension r(na),r1(mn),rr1(amax),rr2(amax)
      do 10 k=lista(1),lista(mfit)
      dyda(k)=0.
10    continue
      i2=(na-lp)-(na-lp)/3
      i3=na-lp
      i4=(na-lp)/3
      do 11 j=lista(1),lista(mfit)
      do 12 j1=1,na
12    r1(j1)=r(j1)
      if(j.gt.i3) goto 30
      if(j.gt.i2) goto 20
      if(j.gt.i4) goto 40

cc    for boundary location parameters   cc

      r1(j)=r(j)+ddd
      call tgw(r1,na,rr1,adata,lp)
      call fff(w1,iww,rr1,rr2,adata,ma1,ma2,iq,ity)
      dyda(j)=(rr2(ii)-yii)/ddd
      goto 11
40    continue

cc    for acoustic impedance parameters   cc

      r1(j)=r(j)+de
      call tgw(r1,na,rr1,adata,lp)
      call fff(w1,iww,rr1,rr2,adata,ma1,ma2,iq,ity)
      dyda(j)=(rr2(ii)-yii)/de
      goto 11
20    continue

cc    for the gradients od the acoustic impedances   cc

      r1(j)=r(j)+dg
      call tgw(r1,na,rr1,adata,lp)
      call fff(w1,iww,rr1,rr2,adata,ma1,ma2,iq,ity)
      dyda(j)=(rr2(ii)-yii)/dg
      goto 11
30    continue

cc    for the constant phase parameter in the redefined wavelet   cc

      if(j.eq.na-(lp-1))then
      r1(j)=r(j)+dp
      dc=dp

cc    for  the linear phase parameter in the redefined wavelet    cc

      else if(j.eq.na-(lp-2))then
      r1(j)=r(j)+ds
      dc=ds

cc    for the quaratic phase parameter in the redefined wavelet   cc

      else if(j.eq.na)then
      r1(j)=r(j)+dad
      dc=dad
      else

c     for the 4 frequency parameters    c

      r1(j)=r(j)+df
      dc=df
      end if
      do 33 j1=1,lp
      pf(j1)=r1(na-lp+j1)
33    continue
      call tgw(r1,na,rr1,adata,lp)
      call waf(w,iww,pf,dt,lp,0.,ity,a,ak)
      call fff(w,iww,rr1,rr2,adata,ma1,ma2,iq,ity)
      if(dc.eq.0.)dc=1.
      dyda(j)=(rr2(ii)-yii)/dc
11    continue
      return
      end

•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
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      subroutine waf(y,lx,pp,dt,lpp,pp4,ity,x,akp)

c  This program is for producing wavelet for forward model in the frequency domain  c

      complex y(lx),y1(1024)
      dimension pp(lpp),x(lx)
c     if(pp4.eq.0.)pp4=0.15
      ity=1
      df=1/(lx*dt)
      af=1/(2*dt)
      pi=3.1415926
      ip1=int(pp(3)/df)
      ip2=int(pp(4)/df)
      ip3=int(pp(5)/df)
      if(pp(6).gt.af)pp(6)=af
      ip4=int(pp(6)/df)
      if(ip1.le.0)ip1=1
      if(ip2-ip1.lt.2)ip2=ip1+2
```

```
        if(ip3-ip2.lt.2)ip3=ip2+2
        if(ip4-ip3.lt.2)ip4=ip3+2
        pp1=(pp(1)/180.)*pi
        pp2=(pp(2)/180.)*pi
        if(ipp.eq.8)then
        pp8=(pp(ipp)/180.)*pi
        else
        pp8=0.
        end if
        do 10 i=1,ip1
        pp3=pp1+pp2*i*df+pp8*(i*df)**2
        if(akp.eq.-1.) then
        yy=x(i)+pp4
        else
        yy=pp(7)*pp4
        x(i)=yy
        end if
10      y1(i)=yy*cexp((0.,1.)*pp3)
        do 20 i=ip1+1,ip2
c       yy=1/(ip2-i+1)
        if(akp.eq.-1.) then
        yy=x(i)+pp4
        else
        yy=pp(7)*((1+cos(pi*(i-ip2)/(ip2-ip1-1)))/2+pp4)
        x(i)=yy
        end if
        pp3=pp1+pp2*(i*df)+pp8*(i*df)**2
20      y1(i)=yy*cexp((0.,1.)*pp3)
        do 30 i=ip2+1,ip3
        pp3=pp1+pp2*(i*df)+pp8*(i*df)**2
        if(akp.eq.-1.) then
        yy=x(i)+pp4
        else
        yy=pp(7)*(1+pp4)
        x(i)=yy
        end if
30      y1(i)=yy*cexp((0.,1.)*pp3)
        do 40 i=ip3+1,ip4
        if(akp.eq.-1.) then
        yy=x(i)+pp4
        else
        yy=pp(7)*((1+cos(pi*(i-ip3)/(ip4-ip3-1)))/2+pp4)
        x(i)=yy



        end if
        pp3=pp1+pp2*i*df+pp8*(i*df)**2
40      y1(i)=yy*cexp((0.,1.)*pp3)
        do 50 i=ip4+1,lx/2
        if(akp.eq.-1.)then
        yy=x(i)+pp4
        else
        yy=pp(7)*pp4
        x(i)=yy
        end if
        pp3=pp1+pp2*(i*df)+pp8*(i*df)**2
50      y1(i)=yy*cexp((0.,1.)*pp3)
        do 11 i=1,lx
        if(i.le.lx/2)then
        y(i)=y1(i)
        else
        y(i)=cmplx(real(y1(lx-i+1)),(-1.)*aimag(y1(lx-i+1)))
        end if
11      continue
        return
        end




**************************************************************
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**************************************************************

        subroutine wa1(y,lx,x,dt,ll)

c       This program is to transfer a wavelet from frequency domain to time domain    c

        complex y(lx),y1(2048)
        dimension x(lx),x1(2048)
        df=1/(lx*dt)
        pi=3.1415926
        ip=5
        do 10 i=1,lx
10      y1(i)=y(i)
        call fft(y1,lx,1)
        do 15 i=1,lx
        if(i.le.lx/2)then
        x1(i)=real(y1(i+lx/2))
        else
        x1(i)=real(y1(i-lx/2))
        end if
15      continue
        amax=0.
        do 12 i=1,lx
        if(abs(x1(i)).gt.amax)then
        amax=abs(x1(i))
        imax=i
        end if
12      continue
        imax=lx/2

c       put a cosine taper to the both sides of the wavelet    c

        if(ll.ne.lx)then
        i1=imax-ll/2+1
        i2=imax+ll/2
        do 16 i=i1,i1+ip
        x1(i)=x1(i1+ip)*(1+cos(pi*(i-i1-ip)/ip))/2
16      continue
        do 17 i=i2-ip,i2
        x1(i)=x1(i2-ip)*(1+cos(pi*(i-i2+ip)/ip))/2
17      continue
        end if

        do 18 i=1,lx
        j=i
        if(ll.ne.lx)j=imax-ll/2+i
        x(i)=x1(j)
18      continue
        return
```

```
        end


**************************************************************
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**************************************************************

ccc     this subroutine used for analysing amplitude and phase spectrum ccc
ccc     and unwrap the phase spectrum in order to get 6 parameters for ccc
ccc     defining the wavelet.                    ccc

        subroutine apw(dt,lt,iwk,xt,pf,lp,x,akp)
        parameter(aminf=15.,amaxf=250.)
        double precision xx,yy,ref,a(3)
        integer lt,if1,if2,if3,if4,l1,i,j,iii,iaa,imax,iwk
        dimension xt(iwk),y(2048),z(2048),xx(2048),yy(2048),pf(lp),x(lt)
        complex x1(2048)
        external e02acf
        intrinsic dble

ccc     'spec.dat' is an amplitude and phase spectrum file    ccc

        open(9,file='spec.dat')
        do 13 i=1,2048
        x1(i)=(0.,0.)
13      xx(i)=0.
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c       this array a is used for phase liner fixing by LAG subroutines    c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
        do 33 i=1,3
33      a(i)=0.
        pi=3.1415926
        df=1./(lt*dt)
        imi1=aminf/df
        ima1=amaxf/df
        l1=lt
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c       change the wavelet's origin to the center of whole length and    c
c       give the original image back in order to do inverse FFT    c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
        do 811 j=1,lt
        if(j.le.iwk/2)then
        x1(j)=cmplx(xt(j+iwk/2))
        else if(j.gt.lt-iwk/2)then
        x1(j)=cmplx(xt(j-lt+iwk/2))
        else
        x1(j)=(0.,0.)
        end if
811     continue

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
        call fft(x1,l1,0)
        do 20 i=1,l1/4
        re=real(x1(i))
        ai=aimag(x1(i))
        x(i)=(re**2+ai**2)**0.5
        if(re.eq.0..and.ai.eq.0.) then
        xx(i)=0.
        else if(re.eq.0..and.ai.gt.0.)then
        xx(i)=90.
        else if(re.eq.0..and.ai.lt.0.)then
        xx(i)=-90.
        else
        xx(i)=(atan(ai/re)/pi)*180.
        end if
        yyi=0.
        if(ai.ge.0.and.re.lt.0)then
        yyi=180.
        else if(ai.le.0.and.re.lt.0)then
        yyi=-180.
        end if
        y(i)=xx(i)+yyi
        if(lp.eq.1)write(9,*)i*df,x(i),y(i)
20      continue
        cmax=0.0
        emax=0.
        do 21 i=imi1,ima1
        emax=(x(i))**2+emax
        if(x(i).gt.cmax) then
        cmax=x(i)
        imax=i
        endif
21      continue
        if(cmax.eq.0.)cmax=1.
        pff1=0.
        pff2=0.
        do 220 i=imax,imi1,-1
        if(x(i).lt.0.8*cmax) then
        if2=i
        goto 221
        end if
220     continue
221     do 198 i=imax,ima1
        if(x(i).lt.0.8*cmax) then
        if3=i
        goto 199
        end if
198     continue
199     do 222 i=if2,imi1,-1
        if(x(i).lt.0.2*cmax) then
        if1=i
        goto 223
        end if
        if(if1.eq.0.)if1=imi1
222     continue
223     do 224 i=if3,ima1
        if(x(i).lt.0.2*cmax) then
        if4=i
        goto 225
        end if
        if(if4.eq.0.)if4=ima1
224     continue
225     continue
        if(if1.le.0)if1=1
        if(if2.eq.if1)if2=if1+2
        if(lp.le.6)goto 999
        j=0
        z(1)=y(1)
        iaa=0
        do 30 i=2,l1/2
        iii=0
```

Left column:

```
           aa1=abs(y(i)-y(i-1))
           if(aa1.ge.180.)then
           if(y(i).lt.y(i-1))iii=1
           if(y(i).gt.y(i-1))iii=-1
           iaa=iaa+iii
           end if
           z(i)=y(i)+360.*iaa
           write(9,*)i*df,x(i),z(i)
30         continue
ccc            In order to get the main information in dominant frequencies,    ccc
ccc            we choose if2 and if3 other than if1 and if4.          ccc

           do 333 i=if2,if3
           j=i-if2+1
           xx(j)=dble(j*df)
           yy(j)=dble(z(i))
333        continue
           imx=if3-if2+1

ccc            e02acf is a NAG FORTRAN LIBRARY subroutine for curve fitting,     ccc
ccc            which calculates a minimax polynomial fit to a set of data points. ccc
ccc            To get a best fitting for the unwraped phase spectrum          ccc

           if(lp.eq.7)then
           call e02acf(xx,yy,imx,a,2,ref)
           pp1=a(1)-a(2)*if2*df
           pp2=a(2)
           else
           call e02acf(xx,yy,imx,a,3,ref)
           pp1=a(1)-a(2)*if2*df+a(3)*(if2*df)**2
           pp2=a(2)-2*a(3)*if2*df
           pf(lp)=a(3)
           end if
999        pf(1)=pp1
           pf(2)=pp2
           pf(3)=if1*df
           pf(4)=if2*df
           pf(5)=if3*df
           pf(6)=if4*df

ccc        If akp=-1, keep the Amplitude Spectrum instead of 4 parameters    ccc

           pf(7)=cmax
           if(pf(4).lt.pf(3))pf(4)=pf(3)+1.
           if(lp.eq.8) then
           write(*,101)(pf(j),j=1,8)
101        format(1x,8f9.4)
           else
           write(*,102)(pf(j),j=1,7)
102        format(1x,7f7.2)
           end if
           close(9)
           return
           end
```

```
ccc   This subroutine is used for carring out forward or inverse Fourier Transform   ccc

           subroutine fft(x,n,inv)
           complex x(n),w,t
           iter=0
           irem=n
10         irem=irem/2
           if(irem.eq.0) go to 20
           iter=iter+1
           go to 10
20         continue
           sign=-1
           if(inv.eq.1) sign=1
           nxp=n
           do 50 it=1,iter
           nxp=nxp2
           nxp2=nxp/2
           pi=3.1415926
           wpwr=pi/float(nxp2)
           do 40 m=1,nxp2
           arg=float(m-1)*wpwr
           w=cmplx(cos(arg),sign*sin(arg))
           do 40 mxp=nxp,n,nxp
           j1=mxp-nxp+m
           j2=j1+nxp2
           t=x(j1)-x(j2)
           x(j1)=x(j1)+x(j2)
40         x(j2)=t*w
50         continue
           n2=n/2
           n1=n-1
           j=1
           do 65 i=1,n1
           if(i.ge.j) go to 55
           t=x(j)
           x(j)=x(i)
           x(i)=t
55         k=n2
60         if(k.ge.j) go to 65
           j=j-k
           k=k/2
           go to 60
65         j=j+k
           if(inv.eq.0) go to 75
           do 70 i=1,n
70         x(i)=x(i)/float(n)
75         continue
           return
           end
```

```
           subroutine fff(w,iwk,x,e,lx,ma1,ma2,iq,idd)
c     this program for producing forward record in frequency domain.
c     x for reflected coefficients,w for seismic wavelet,e for output.
           parameter(max=2048)
```

Right column:

```
           complex w(iwk)
           complex x1(max)
           dimension e(lx),x(lx)
           do 6 i=1,lx
                  e(i)=0.
6          x1(i)=cmplx(x(i))
                  call fft(x1,lx,0)
           do 20 i=1,lx
20         x1(i)=x1(i)*w(i)
           call fft(x1,lx,1)
           if(idd.eq.1) then
                  do 30 i=1,lx
                  if(i+iq.lt.ma1.or.i+iq.gt.ma2)goto 30
                  e(i+iq)=real(x1(i))
30         continue
           else
                  do 40 i=ma1,ma2
40         e(i)=real(x1(i))
           end if

           return
           end
```

```
           subroutine tgw(r1,lt1,r,lt,lp)
           parameter(ma=50,nmax=2048)

C     this subroutine is to produce a reflected coefficients series    C

           dimension e(ma),t(ma),r(lt),ee(nmax),r1(lt1),g(ma)
                  nla=(lt1-lp)/3
           do 5 k=1,nla
                  g(k)=r1(k+2*nla)
           e(k)=r1(k+nla)
5          t(k)=r1(k)
           i=0
           do 10 j=1,nla
           if(i.eq.0)then
           i1=1
           goto 15
           endif
           i1=int(t(j)+0.1)+1
15         i=i+1
           i2=int(t(j)+0.1)
           do 20 k=i1,i2
           ee(k)=e(j)+g(j)*(k-i1)
20         continue
10         continue
           i3=int(t(nla))
           do 40 i=1,i3-1
           r(i)=(ee(i+1)-ee(i))/(ee(i+1)+ee(i))
40         continue
           r(i3)=0.
           if(i3.lt.lt) then
           do 50 i=i3+1,lt
           r(i)=0.
50         continue
           end if
           return
           end
```

```
           subroutine wtg(r1,lt1,r,lt,lp)
           parameter(ma=50,nmax=2048)

C     this subroutine is to produce an acoustic impedance series    C

           dimension e(ma),t(ma),r(lt),r1(lt1),g(ma)
                  nla=(lt1-lp)/3
           do 5 k=1,nla
                  g(k)=r1(k+2*nla)
           e(k)=r1(k+nla)
5          t(k)=r1(k)
           i=0
           do 10 j=1,nla
           if(i.eq.0)then
           i1=1
           goto 15
           endif
           i1=int(t(j)+0.1)+1
15         i=i+1
           i2=int(t(j)+0.1)
           do 20 k=i1,i2
           r(k)=e(j)+g(j)*(k-i1)
20         continue
10         continue
           i3=int(t(nla)+0.5)
           if(i3.lt.lt) then
           do 50 i=i3+1,lt
           r(i)=r(1)
50         continue
           end if
           return
           end
```

```
C   ppp.dat  is a input data file to used for synthetic examples by using GLI   C
C   with noise free or with some white noise, the main programm is in pp.       C

result0,749,40,1,40,40,9,n,tp2.dat, (f1,e1,nm0,nm1,nm2,nmw,nlm,flf)
```

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```
eee.dat,gee1.dat,result5,12.0,5.0,0.3,18,2,554,8,y (ea,em,ga,mtg,jm,lp,whi)
n,3,28,35,0.00001, (GLI wavelet inversion:ff,ig0,mf1,mf2,almda)
0.0,0.0,0.0,0.0,0, (fixed or inverted)
n,1,300,470,0.01,  (location inversion in time:ftg,ig1,mg1,mg2,almda00)
y,2,1,9,.001, (location inversion in frequency:ftn,in1,mn1,mn2,almda11)
0.0,0.0,0.0,0.0,0.0,9,0,11,0,13,0,0,0,0,0,19 (fixed or inverted)
y,2,10,27,.01, (acostic impedance inversion:fth,ih1,mh1,mh2,almda22)
10,11,0,13,0,15,0,17,0,19,20,0,0,0,0,0,26,27, (fixed or inverted)
n,2,19,27,.001, (gradients of acoustic impedance:fti,ii1,mi1,mi2,almda33)
19,20,0,0,0,0,0,26,27,0,0, (fixed or inverted)
y,1,28,35,.00001,  (wavelet inversion in F-domain:ftj,ij1,mj1,mj2,almda44)
0,0,0,0,0,0,0,0,  (fixed or inverted)
0,8,70,15,21,15,21,8,77
0.001,512,32,9,2,9,0,0,0.,  (dt,lt,iwk,na,iq,mm,lk,itj,akp)
.301,.304,.370,.380,.410,.419,.432,.435,.512
7.6,4.,8.6,4.,6.0,4.,5.6,4.,7.6,4.,7.6,4.,7.6,4.,7.6,4.,7.6,4.,7.6,4.,7.6,
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
y,89.,0.13,15.,36.,89.,201.,1.0,-0.002


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      program iapp

c    The program is a GLI for synthetic examples with noise free or white noise    c
c------------ it is similar to program iadd in some way, reader can refer to it. ----------c

     complex w(1024),w2(1024),w1(1024)
     common /wavelet/ddd,de,dg,dp,ds,df,dad,lp,ga,ea,em
     parameter(jt=1024,jp=1024,jl=40,np=10)
     dimension r(jt),e1(jt),r1(jp),lista(jp),r2(jt),pf2(np),ifix(jp),
    *error(50),rr(jp),e3(jt),e0(jp),g1(jt),pf1(np),r2(jp),a(jt),y1(jt)
     dimension covar(jp,jp),alpha(jp,jp),iti(jt),r4(jp),f(jt),f2(jt)
    * ,aol(jp),e(jt),anee(500),e2(jt),t3(jt),ee(jt),ifix1(jp),f1(jt)
     dimension mat(jt)
                double precision e4(jt)
                character ftg*1,fth*1,fti*1,ff1*7,ff2*8,ff0*7,fcj*1,fi1*1,ff*1
    *              ,fin*1,ff3*7,ff4*7,fol*1,ff6*1,whi*1
                dimension f1(jt)
                external g05cbf,g05fdf
c-------Give initial values for iterative parameters-------c

                ane=.1

c------ppp.dat is a file for all input parameters-------c

                open(4,file='ppp.dat',status='old')

c-- ff0:seismic trace file; al:trace length; am0:first trace No.  --c
c-- am1:interval trace No.; am2:last trace No. to inverse ---c
c-- amw:No. of trace which is nearest Well--c
c alm:No. of known layers; ftl:'y' fix extracted wavelet & inverse locations c

                read(4,76)ff0,al,am0,am1,am2,amw,alm,ftl,ff4
76              format(a7,1x,6i5,a1,1x,a7)


c-------- ff1:result file for plotting;  ff2:result file for looking; ----------c
c----- ea,em:marxism and minimum values of acoustic impedance -------c
c-- if whi:'y' then 15 % white noise is added to the synthetic trace ----c

                read(4,78)ff1,ff2,ff3,ea,em,ga,mtg,jm,lp,whi
78              format(a7,1x,a8,1x,a7,1x,3f6.2,3i4,a1)

ccccc Following parameters used for inversing iterations  ccccc

                read(4,79)ftf,ig0,mf1,mf2,almda01
                read(4,*)(ifix1(i),i=mf1,mf2)
                read(4,79)ftg,ig1,mg1,mg2,almda00
                read(4,*)(ifix(i),i=mn1,mn2)
                read(4,79)fth,in1,mn1,mn2,almda11
                read(4,*)(ifix(i),i=mn1,mn2)
                read(4,79)fth,ih1,mh1,mh2,almda22
                read(4,*)(ifix(i),i=mh1,mh2)
                read(4,79)fti,ii1,mi1,mi2,almda33
                read(4,*)(ifix(i),i=mi1,mi2)
                read(4,79)ftj,ij1,mj1,mj2,almda44
                read(4,*)(ifix(i),i=mj1,mj2)
79              format(a1,1x,3i4,f12.10)
                read(4,*)(mh(j),j=1,alm)

cccc dt:sample rate; lt:processing length; iwk:wavelet length;       cccc
cccc na:no. of layers of guess; iqq:searching range; mm:No. of layers of  ccc
cccc inversion; lk:time shift range; itj:test parameter for time shift.      ccc

        read(4,*)dt,lt,iwk,na,iqq,mm,lk,itj,akp

ccc calculating range of inversing parameters  ccc

                if(ftl.eq.'y')fol='y'

                am=am0
                mgg=mg2-mg1
                almda0=almda00
                almda1=almda11
                almda2=almda22
                almda3=almda33
                almda4=almda44
                write(*,*)'this is iapp program for synthetic example'
                open(2,file=ff1,access='direct',recl=4*lt)
                itg=0
                atg=0
itee=0
                itef=0
                itg1=0
                itg2=0
                itg3=0
                itg4=0
                ity=1
                mg0=mg1
                maa=mn2-mn1
                mhh=mh2-mh1
                mii=mi2-mi1
                mjj=mj2-mj1+1
                mmm=mm
                iww=lt
                iq=iwk/2
```

```
                lt1=lt-iwk+1
                lt2=3*alm+lp
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      For next observed trace inversion and continuous inversin      c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      Note:every time am should equal to the value  last time         c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
122             continue
                pp4=0.
                if(am.eq.amw)then

cccccccccccccccccccccc  Synthetic Case   cccccccccccccccccccccc

                open(9,file=ff0,status='old')
          read(9,*)ijf,lpn
          read(9,*)(t3(k),k=1,alm)
                read(9,*)(e3(k),k=1,alm)
          read(9,*)(g1(k),k=1,alm)
                read(9,*)(pf1(k),k=1,lp)
                close(9)
                open(9,file='wavelet')
                call waf(w,lt,pf1,dt,lp,0.0,ity,a,0)
                df=1/(lt*dt)
                do 918 j=1,lt
                dfi=df*j
                write(9,*)dfi,a(j)
918             continue
                pause
                call waf(w,lt,f2,dt,iwk)
                write(2,rec=1)(f2(j),j=1,lt)
          do 731 k=1,alm
                rr(k)=t3(k)/dt
                rr(k+2*alm)=g1(k)
                rr(k+alm)=e3(k)
731             continue
          do 706 k=1,lp
706             rr(3*alm+k)=pf1(k)
                call tgw(rr,lt2,r,lt,lp)
                call fff(w,lt,r,e1,lt,mg1,mg2,iq,ity)
                ama=0.
                do 735 j=1,lt
                e2(j)=e1(j+itj)
                ama=e1(j)*e1(j)+ama
735             continue
                do 737 j=1,lt
                e1(j)=e2(j)
                e2(j)=0.
737             continue

c  Subrintine g05 is a nag subroutine for generating a white Gaussian distribution noise  c

                if(whi.eq.'y') then
                write(*,*)'enter g05 subroutine'
                call g05cbf(0)
                call g05fdf(-1.0,1.0,lt,e4)
                do 783 j=1,lt
783             e2(j)=e4(j)
                amg=0.
                bmg=0.
                do 780 j=mg1,mg2
                amg=(e2(j))**2+amg
780             continue
                cmg=0.15*sqrt(ama/amg)
                dmg=0.
                do 781 j=mg1,mg2
                e2(j)=cmg*e2(j)
                dmg=(e2(j))**2+dmg
781             continue
                write(*,*)'SNR===',sqrt(dmg/ama)
                do 782 j=mg1,mg2
                e1(j)=e1(j)+e2(j)
782             continue
                end if
                write(2,rec=2)(e1(j),j=1,lt)
                call wtg(rr,lt2,e,lt,lp)
                write(2,rec=3)(e(k),k=1,lt)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccc  read initial guess for the inverse model  cccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                read(4,*)(t2(k),k=1,na)
                read(4,*)(e3(k),k=1,na)
                read(4,*)(g1(k),k=1,na)
                read(4,571)ff6,(pf2(k),k=1,lp)
571             format(a1,1x,8f8.4)
                if(ff6.eq.'y') then
                pff1=pf2(3)
                pff2=pf2(4)
                pff3=pf2(5)
                pff4=pf2(6)
                if(ff.eq.'y') then
                do 666 k=1,lp
666             pf1(k)=pf2(k)
                end if
                call waf(w,lt,pf2,dt,lp,pp4,ity,a,0.)
                call wat(w,lt,f1,dt,iwk)
          do 587 i1=1,iwk
                i2=i1
587             f(i1)=f1(i2)
                call tgw(rr,lt2,r,lt,lp)
                call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)
                anta=0.
                aqq=0.
                do 484 i=mg1,mg2
                ama=ama+e1(i)**2
                aqq=aqq+e2(i)**2
                anta=e1(i)*e2(i)+anta
                anta=(e2(i)-e1(i))**2+anta
484             continue
                cc=sqrt(anta**2/(ama*aqq))
                anta=(anta/ama)*100.
                mg0=mg1
                end if
                close(4)
                end if

ccccccccccccccccccccccccccccccccccccccccccccccccccc
c   get the real reflected coefficients       c
ccccccccccccccccccccccccccccccccccccccccccccccccccc
```

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```
                    if(ff0.ne.'result0')then                                    do 437 k=1,lt2
                    r(1)=0.                                        437         r1(k)=rr(k)
                    do 712 j=2,lr                                              call wtg(rr,lt2,ee,lt,lp)
                    r(j)=(e(j)+e(j-1))/(e(j)+e(j-1))                           write(2,rec=5)(ee(j),j=1,lt)
712                 continue                                                   if(flg.eq.'a')mm=aa
                    else                                                     call tgw(rr,lt2,r2,lt,lp)
                    call tgw(rr,lt2,r,lt,lp)                                    call fff(w1,lt,r2,e0,lt,mg1,mg2,iq,ity)
                    end if                                                     write(2,rec=8)(e0(j),j=1,lt)
c                                                            c
c                                                                            j2=j2+1
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc            izq=0
c--   Using Wiener Shaping Filter to extract wavelet,calculate time shift  --c  1111    lt1=lt-iwk+1
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc            dg=0.001
                                                                             ds=0.001
           if(nm.eq.nmw.and.ff6.ne.'y')then                                  dad=.0001
               mp1=mg1-lk                                                     ddd=1.0
               mp2=mg2+lk                                                     de=0.001
       acc=0.                                                                 df=1./(lt*dt)
           do 404 i=1,2*lk+1                                                  dp=.01
                    jj=(i-lk-1)                                               ite1=0
                    do 409 j=1,lt
409                 e0(j)=0.                                       c This step(iii=1)is to inverse boundaries using GLI(time) fixing wavelet c
                    do 443 j=1,lt
                    k=j+jj                                                         if(flg.eq.'y')then
                    if(k.le.0.or.k.gt.lt) goto 443                               ggg=0.
443                 e0(k)=e1(j)                                                  iii=1
                    call ext1(r,mg1,mg2,e0,mg1,mg2+iwk-1,f,1,iwk)                 goto 989
                    do 810 j=1,lt                                                end if
                    if(j.le.iwk)then
                    w(j)=cmplx(f(j))                              c This step(iii=2)is to inverse boundaries using GLI(frequency)fix wavelet c
                    else
                    w(j)=(0.,0.)                                  999    if(ff1.eq.'y'.and.nm.eq.nmw)then
                    end if                                                   ggg=1.
810                 continue                                                 iii=2
                    ity=0                                                    goto 989
                    call fft(w,lt,0)                                          end if
                    call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)         ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
           anee(i)=0.
               aqq=0.                                             1000    continue
               ama=0.                                                        itee=0
           do 442 j=mg1,mg2
                    aqq=aqq+e2(j)**2                              cccccc The second step(iii=2) is to inverse other parapeters using GLI cccccc
                    ama=ama+e0(j)**2
           anee(i)=anee(i)+(e0(j)-e2(j))**2                                  call tgw(r1,lt2,r,lt,lp)
442                 continue                                                 if(ffj.eq.'y'.or.(ff.eq.'y'.and.nm.eq.nmw))then
c          write(*,*)'i,ama,aqq,anee',i-lk-1,ama,aqq,anee(i)                 if(ff6.eq.'n')call apw(dt,lt,iwk,f,pf2,lp,a)
404                 continue                                                 call waf(w,lt,pf2,dt,lp,0,ity,a,akp)
           amin=10000.                                                       do 386 i=1,lt
           do 441 i=1,2*lk+1                                     386         w1(i)=w(i)
           if(anee(i).lt.amin)then                                          call wa(w1,lt,f2,dt,iwk)
               amin=anee(i)                                                 write(2,rec=9) (f2(j),j=1,iwk)
               imin=i                                                 do 397 k=1,lp
           end if                                              397    r1(3*nn+k)=pf2(k)
441                 continue                                                 do 387 i1=1,iwk
           write(*,*)'imin==',imin-lk-1                                      i2=i1
                    lpa=imin-lk-1                               387         f(i1)=f2(i2)
           do 448 j=1,lt                                                     end if
                    e2(j)=0.                                                 call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)
448                 continue                                     if(flg.eq.'y'.and.cpre.ge.0.6)then
                    do 449 j=1,lt                                            cpre=0.5
                    f(j)=0.                                          ggg=0.
                    jj=j+lpa                                        iii=1
                    if(jj.lt.0.or.jj.gt.lt) goto 449                 goto 989
           e2(jj)=e1(j)                                                      end if
449                 continue                                     388         ama=0.
                    do 455 j=1,mg1-1                                         ama=0.
455                 e1(j)=0.                                                 anta=0.
                    do 456 j=mg2+1,lt                                        aqq=0.
456                 e1(j)=0.                                                 do 313 i=mg1,mg2
                    do 447 j=mg1,mg2                                         ama=(e1(i))**2+ama
447                 e1(j)=e2(j)                                              aqq=(e2(i))**2+aqq
           call ext1(r,mg1,mg2,e1,mg1,mg2+iwk-1,f,1,iwk)                     anta=e1(i)*e2(i)+anta
                    write(2,rec=7)(f(j),j=1,iwk)                             antn=(e2(i)-e1(i))**2+antn
                    do 811 j=1,lt                              313           continue
                    if(j.le.iwk) then                                        write(*,*)'Best initial N/S Ratio',antn/aqq
                    w(j)=cmplx(f(j))                                         cc=sqrt(anta**2/(ama*aqq))
                    else                                                     anta=(anta/ama)*100.
                    w(j)=(0.,0.)                                             write(*,*)'Best Correlte Coefficient==',cc
                    end if                                                   write(*,*)'Energy of Observed,forward and Error:',ama,aqq,antn
811                 continue                                    988           continue
                    ity=0                                                    if(ff.eq.'y'.and.nm.eq.nmw)then
                    call fft(w,lt,0)                                         ggg=-1.
                    call fff(w,lt,r,e2,lt,mg1,mg2,iq,ity)                    else if(fla.eq.'y') then
                    write(*,*)'This wavelet extracted by Wiener Shaping Filter'  ggg=1.
               antn=0.                                                       else if(flb.eq.'y') then
               ama=0.                                                        ggg=2.
               anta=0.                                                       else if(fli.eq.'y') then
               aqq=0.                                                        ggg=3.
           do 414 i=mg1,mg2                                                  else if(flj.eq.'y') then
                    ama=ama+e1(i)**2                                 ggg=4.
                    aqq=aqq+e2(i)**2                                         end if
                    anta=e1(i)*e2(i)+anta                                    iii=2
               anta=(e2(i)-e1(i))**2+anta                                    itit=1
414                 continue                                                 ltt=lt
                    cc=sqrt(anta**2/(ama*aqq))                    989           continue
                    write(*,*)'Best initial N/S Ratio',anta/aqq   400           if(iii.eq.1)ll=nn
                    anta=(anta/ama)*100.                             if(iii.ge.2)ll=mm
                    write(*,*)'Best Correlte Coefficient==',cc      if(flg.eq.'a'.and.iii.ge.2)ll=nn
                    write(*,*)'Ene. of Observed,forward,Error(%):',ama,aqq,anta  lt2=3*ll+lp
                    end if                                                   itit=1
                                                                            if(iii.eq.2)call tgw(rr,lt2,r,lt,lp)
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc           if(iii.ge.2) then
cccccccccccccc    Prepare to inverse data in two steps    cccccccccccc        ll=lt2
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc            if(ff1.eq.'y'.and.nm.eq.nmw.or.nm.ne.nmw)then
                                                                             if(izq.eq.0)then
ccccc First step(iii=1) is to locate the positions of desired layers ccccc   do 445 i=1,lt2
ccc Either in frequency domain or time domain depending on ff1 or flg  ccc    445           r1(i)=rr(i)
                                                                             end if
791                 lt2=3*nn+lp                                             end if
c                                                                           else
c                   nhw=0                                                    ll=lt
c                   nhw=mod(nm-nmw+nm1,4*nm1)                                do 446 i=1,lt
                    open(3,file=ff2)                              446         r1(i)=0.
                    e00=e3(1)                                                end if
           do 450 k=1,nn
                    rr(k)=t2(k)/dt                               ccccc Set an initial error value as large as possible ccccc
                    rr(k+2*nn)=g1(k)
450                 rr(k+nn)=e3(k)                               c     emin=0.
                    do 436 k=1,lp                                            emax=10000.
436                 rr(3*nn+k)=pf2(k)                            ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                                                                210           if(ntg.ge.mtg)goto 211
```

118

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
ccc For each different iterations,to set different iterative parameters ccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

212    if(ftg.eq.'y'.and.ggg.eq.0.)then
                itg=ig1
                almda=almda0
        mal=mg1
                    ma2=mg2
            else if(ftl.eq.'y'.and.ggg.eq.1..and.am.eq.nmw)then
                itg=ia1
                almda=almda1

                mal=mal
                ma2=ma2
            else if(ftl.eq.'y'.and.ggg.eq.-1..and.am.eq.nmw) then
                itg=ig0
                almda=almda01
                mal=mf1
                ma2=mf2
                ftf='n'
        else if(ftn.eq.'y'.and.ggg.eq.1.)then
                itg1=ia1
                itg=itg+itg1
                if(izq.eq.1.and.izp.eq.1)almda1=almda1/100.
                almda=almda1
                mal=mal
                ma2=ma2
                izp=0
            else if(fth.eq.'y'.and.ggg.eq.2.)then
            itg2=ih1
                itg=itg+itg2
        mal=mh1
        ma2=mh2
                almda=almda2
            else if(fti.eq.'y'.and.ggg.eq.3.)then
                itg3=ii1
                itg=itg+itg3
                            mal=mi1
                            ma2=mi2
                    almda=almda3
            else if(ftj.eq.'y'.and.ggg.eq.4.)then
                itg4=ij1
                itg=itg+itg4
                            mal=mj1
                            ma2=mj2
                    almda=almda4
                end if
        j=0
                if(am.eq.nmw.and.ggg.eq.2) ane=0.
                do 465 i=mal,ma2
                if(ggg.ge.1.)then
                if(ifix(i).eq.i)goto 465
                else if(ggg.eq.-1.) then
                if(ifix1(i).eq.i)goto 465
                end if
        j=j+1
                if(am.eq.nmw.and.ggg.eq.2)ane=ane+r1(i)**2
        lista(j)=i
465        continue
                    ma=j
500      iter=itee
                    itee=itg
600      iter=iter+1
                if(iter.eq.1.or.iter.eq.1+itef)aa=-1.
c                if(iter.eq.1)aa=-1.

cc Decide how to apply a initial inversion (itef=itg means apply it before
cccc every step,itef=0 means apply it only before the first step) ccccc

                    itef=itg
c        itef=0
cccc nmw+0 means the interval is null otherwise can do this repeatly cccc
                if(ftg.eq.'y'.and.ggg.eq.0.)then

cccccccccccccc This is the first inversion step ccccccccccccc
                    do 747 i=1,lt
                    if(i.le.lt-iwk)then
                    r1(i)=0.
                    else
                    il=i-lt+iwk
c                    i2=lt/2-iwk/2+il
                    r1(i)=f(il)
                    end if
747        continue
                    do 746 j=1,iwk
c                    j1=lt/2-iwk/2+j
746            w2(j)=cmplx(f(j))
                if(iter.eq.1)bb=emax
        call mqw(e1,lt,r1,l1,lista,ma,covar,alpha,ma,er,aa,bb,akp
    * ,cc,dt,ggg,w2,iwk,iww,ama,mg1,mg2,mah,almda,iq,ity,y1,y1)

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

                    er=1.
                    do 345 i=1,ma
                    lista(i)=0.
                    do 346 j=1,ma
                    covar(i,j)=0.
                    alpha(i,j)=0.
346        continue
345        continue
        else
cccccccccccc This is the second inversion step ccccccccccccccccc

                if(iter.eq.1)bb=emax
        call mqw(e1,lt,r1,l1,lista,ma,covar,alpha,ma,er,aa,bb,akp
    * ,cc,dt,ggg,w,iwk,iww,ama,mg1,mg2,mah,almda,iq,ity,a,ee)
                    almda=aa

cccccccc if use similarity as a criterio other than error,then
cccccccc It change to gi and emax to emin .

                    error(itit)=bb
                end if
                if(ggg.eq.0.)then
                if(iter.lt.itg)goto 600
                goto 555
                end if
502        continue
```

```
                if(error(itit).lt.emax)emax=error(itit)
                itit=itit+1
                if(iter.ge.itg) then
                        if(ftl.eq.'y'.or.ftf.eq.'y') then
                        if(am.eq.nmw) then
                        itg=0
                        iter=0
                        end if
                        end if
                        goto 504
                    else
                goto 600
                        end if
555        continue
                if(ftg.eq.'y'.and.ggg.eq.0.)then

ccccccccccc Automatically picking up the preset No. of layers due to cccccccccc
cccccccccccccccc the relative large amplitudes in the spiked trace cccccccccccc

                        do 172 i=1,ma1-1
                        r2(i)=0
172            r1(i)=0.
                        do 173 i=ma2,lt
                        r2(i)=0.
173            r1(i)=0.
                        amax=0.
                        rmax1=0.
                        do 157 i=ma1,ma2
                        r2(i)=0.
                        r4(i)=r1(i)
157            continue
                        write(2,rec=8)(r1(j),j=1,lt)
                        iqq1=iqq
153            k=0
            do 155 i=ma1,ma2
                        max=1
                        do 154 j=i-iqq1,i+iqq1
                        if(j.eq.i)goto 154
                        if(abs(r4(i)).gt.abs(r1(j)))then
                        if(max.ne.0)max=-1
                        else
                        max=0
                        end if
154            continue
                        if(max.eq.-1.)then
                        k=k+1
                                    nol(k)=i
                                    endif
155        continue
                        if(k.lt.mm) then
                        iqq1=iqq1-1
                        goto 153
                        end if
                        write(*,*)'no. of layers(calculate and preset)',k,mm
                        write(*,*)(nol(i),i=1,k)
90            do 91 j=1,mm-1
                        amax=0.
                        do 92 i=1,k
                        ampr=abs(r4(nol(i)))
                        if(ampr.gt.amax)then
                        amax=ampr
                        tty=nol(i)*dt
                        iti(j)=i
                        end if
92            continue
                        r4(nol(iti(j)))=0.
                        t3(j)=tty
91            continue
                        do 98 i=mm-1,1,-1
                        amax=0.
                        do 97 j=1,mm-1
                        if(t3(j).gt.amax)then
                        amax=t3(j)
                        j1=j
                        end if
97            continue
                        t3(j1)=0.
                        t1(i)=amax
98            continue
                        amed=15*dt
                        do 93 i=1,mm-1
                        amint=t1(i)-t2(i)
                        write(*,*)t1,t2,t1(i),t2(i)
                        ilx=0
                        if(abs(amint).gt.amed.and.amint.lt.0)then
                        do 99 j=1,k
                        if(ilx.eq.1) goto 99
                        if(abs(nol(j)*dt-t2(i)).le.amed)then
                        t1(i)=nol(j)*dt
                        ilx=1
                        end if
99            continue
                        else if(abs(amint).gt.amed.and.amint.gt.0) then
                        do 299 j=k,1,-1
                        if(ilx.eq.1) goto 299
                        if(abs(nol(j)*dt-t2(i)).le.amed)then
                        t1(i)=nol(j)*dt
                        ilx=1
                        end if
299            continue
                        end if
93            continue
                        do 95 i=1,mm-1
95            t2(i)=t1(i)
                do 511 i=1,mm
                r1(i)=t2(i)/dt
                        r1(i+2*mm)=g1(i)
                        if(i.gt.nn)e3(i)=e3(nn)
511            r1(i+mm)=e3(i)
                do 512 i=1,lp
512            r1(3*mm+i)=pf2(i)
                        write(*,*)(r1(i),i=1,mm)
                write(3,*)'ERROR ',er,' SIMILARITY ',cc,' TRACE ',am
                write(3,*)' guess location      inversion location'
                        do 517 i=1,mm
                        if(i.gt.nn)then
                        write(3,103)i,r1(i)*dt,r1(i+mm),r1(i+2*mm)
                        else
                        write(3,101)i,rr(i)*dt,rr(i+ll),rr(i+2*ll),r1(i)*dt,
    *        r1(i+mm),r1(i+2*mm)
                        end if
```

```
517              continue
      do 518 i=1,lp
518      write(3,102)i+ll*3,rr(i+ll*3),r1(i+mm*3)
          if(iter.lt.itg) goto 600
          izq=1
                goto 999
          endif
504    continue

cccccccccc Save the individual damping factors for each iteration ccccccccccc

              if(ggg.eq.-1.)almda01=aa
      if(ggg.eq.1.)almda1=aa
      if(ggg.eq.2.)almda2=aa
      if(ggg.eq.3.)almda3=aa
              if(ggg.eq.4.)almda4=aa
              if(fti.eq.'y'.and.nm.eq.nmw)then
                      ggg=-1
                      ma1=mf1
                      ma2=mf2
              fti='n'
                      goto 1000
              end if
              if(fti.eq.'y'.and.ggg.lt.1.)then
                  ggg=1.
                  ma1=mn1
                  ma2=mn2
                  goto 212
              end if
              if(fti.eq.'y'.and.ggg.lt.2.)then
                  fti='n'
                  ggg=2.
                  ma1=mh1
                  ma2=mh2
                  goto 212
              end if
      if(fti.eq.'y'.and.ggg.lt.3.)then
              fti='n'
              ggg=3.
              ma1=mi1
              ma2=mi2
              goto 212
      end if
      if(fti.eq.'y'.and.ggg.lt.4.)then
          fti='n'
          ggg=4.
          ma1=mj1
          ma2=mj2
          goto 212
      end if

cccc        Normally for location of the boundarys,it is better just inverse cccc
cccc        it at the very begining,i.e. it is not necessary to repeat it.But cccc
cccc        when the time domein invesion is introduced,it may be worth to repeat.

              if(ftn.eq.'y')then
              ggg=1.
              goto 233
              end if
              if(fth.eq.'y')then
              ggg=2.
              goto 233
              else if(fti.eq.'y')then
              ggg=3.
              goto 233
              else if(ftj.eq.'y') then
              ggg=4.
              end if
233    ntg=ntg+1
              goto 210
520            write(3,*)'error is less than expected'
              goto 530
211            write(3,*)'iterative time reached preset value'

ccccc  Write the inverse result,some of them for next trace invesion ccccc

530            continue
cc             If the inverted results is not better than previous guess,keep the
cc             previous inverted results .
      write(3,*)'ITER',itit-1,' ERR',er,' SIMILAR',cc,' TRA',nm
      write(3,*)' guess location and impedance   inversion results'
              do 199 i=1,ll
      write(3,101)i,rr(i)*dt,rr(i+ll),rr(i+2*ll),r1(i)*dt,r1 (i+ll),
     *        r1(i+2*ll)
199    continue
      do 198 i=1,lp
198    write(3,102)i,rr(i+3*ll),r1(i+3*ll)
101    format(1x,i4,2x,f9.5,2x,f9.5,2x,f9.5,2x,f9.5,2x,f9.5)
102    format(1x,i4,2x,f10.5,2x,f10.5)
103            format(1x,i4,35x,f9.5,2x,f9.5,2x,f9.5)
              lt2=3*mm+lp
              if(ftj.eq.'y'.or.fol.eq.'y')then
              write(*,*)'enter output'
              do 526 i=1,lp
526    pf2(i)=r1(3*mm+i)
              call waf(w,lt,pf2,dt,lp,0,,ity,a,akp)
              call wat(w,lt,f1,dt,iwk)
              do 527 i=1,iwk
c             i1=lt/2-iwk/2+i
              i1=i
              f(i)=f1(i1)
527            continue
              write(2,rec=11)(f(j),j=1,iwk)
              end if
              open(4,file=ff3,status='old')
              write(4,*)nm,lpe,ama,ane
              write(4,*)(r1(j)*dt,j=1,mm)
              write(4,*)(r1(j),j=mm+1,2*mm)
              write(4,*)(r1(j),j=2*mm+1,3*mm)
              write(4,*)(r1(j),j=3*mm+1,3*mm+lp)
              write(4,*)(w(j),j=1,iww)
              write(4,*)(f(j),j=1,iwk)
              close(4)
              write(*,*)(r1(j),j=1,lt2)

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c              OUTPUT RESULTS                              c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

              call tgw(r1,lt2,r,lt,lp)
              call ftf(w,lt,r,e0,lt,mg1,mg2,iq,ity)
```

```
              write(2,rec=12)(e0(i),i=1,lt)
              arr0=0.
              do 459 i=1,lt
              if(abs(e0(i)).gt.arr0)arr0=abs(e0(i))
459            continue
              ee(1)=arr0
              write(2,rec=10)(ee(j),j=1,lt)
              call wtg(r1,lt2,r,lt,lp)
              write(2,rec=13)(r(j),j=1,lt)
              write(2,rec=14)
              if(nm.eq.nmw) then
              arr0=0.
              arr1=0.
              arr2=0.
              arr3=0.
              anls=0.
              do 533 i=mg1,mg2
              anls=(e2(i))**2+anls
              arr0=(e0(i))**2+arr0
              arr1=(e2(i)-e0(i))**2+arr1
              arr2=(r(i)-e(i))**2+arr2
              arr3=(e(i))**2+arr3
533            continue
              write(3,*)'N/S ratio after inversion :',sqrt(arr1/aqq)
              write(3,*)'RMS impedance error =====',sqrt(arr2/arr3)
              write(*,*)'N/S ratio after inversion :',sqrt(arr1/aqq)
              write(*,*)'RMS impedance error =====',sqrt(arr2/arr3)
              end if
              nm=nm+nm1
      close(2)
      stop
      end


•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
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c  Program plot0 is used for plotting the inversion results by using UNIRAS libary   c

      PROGRAM PLOT0
      REAL PLOT(751,801),TRACE(751)
      REAL POSX(3),POSY(3),CLASS(3)
      CHARACTER FF*7
      INTEGER NFIRST(751)
      CHARACTER*60 TITLE

C    READ FILENAME FROM SCREEN
      WRITE(6,*)'PLEASE INPUT FILENAME YOU WANT TO PLOTTING'
      READ(5,777)FF
777  FORMAT(A7)
      write(6,777)ff

C    First some defaults
C    These will only be picked up on the first call to the subroutine
C    Later calls will remember specified input

      IF (IFTR.EQ.0)IFTR = 1
      IF (ILTR.EQ.0)ILTR = 14
      IF (IFPO.EQ.0)IFPO = 1
      IF (ILPO.EQ.0)ILPO = 750
      IF (IVA.EQ.0)IVA = 1
      IF (IPOL.EQ.0)IPOL = 1
      IF (IWIG.EQ.0)IWIG = 1
      IF (DX.EQ.0)DX = 1
      IF (DZ.EQ.0)DZ = 1000
      IF (DEFL.EQ.0)DEFL = 1.0
      IF (IMODE.EQ.0)IMODE = 1
      IF (NZ.EQ.0)NZ = 1500
      IJK=1
      INOR=1

300  WRITE(6,301)
      WRITE(6,302)IFTR,ILTR,inte
      WRITE(6,303)IFPO,ILPO,NZ
      WRITE(6,304)IVA
      WRITE(6,305)IPOL
      WRITE(6,306)IWIG
      WRITE(6,307)DX
      WRITE(6,308)DZ
      WRITE(6,309)IDORT
      WRITE(6,310)DEFL
      WRITE(6,311)ITRSC
      WRITE(6,312)TRSC
      WRITE(6,313)IAOC
      WRITE(6,314)IMODE
      WRITE(6,315)IFB
      WRITE(6,316)INOR
      WRITE(6,317)ITITLE
      WRITE(6,318)ICONT
      WRITE(6,320)

301  FORMAT(' 1.   OK ! go  ')
302  FORMAT(' 2.   First/last/integral traces to plot: ',3I5)
303  FORMAT(' 3.   First/last/total samples to plot : ',3I5)
304  FORMAT(' 4.   Variable area (1=yes)      : ',I4)
305  FORMAT(' 5.   Polarity (1=SEG norm)      : ',I4)
306  FORMAT(' 6.   Wiggle trace (1=yes)       : ',I4)
307  FORMAT(' 7.   Trace separation  in m      : ',F7.3)
308  FORMAT(' 8.   DZ in m or DT in microsec     : ',F8.3)
309  FORMAT(' 9.   Plotting depth(1) or time(0)   : ',I4)
310  FORMAT(' 10.  Max tr deflec in tr spacing    : ',F8.3)
311  FORMAT(' 11.  True scale plot (1=yes)      : ',I4)
312  FORMAT(' 12.  True scale scalar (eg 3=>1m=3mm) : ',F8.3)
313  FORMAT(' 13.  AGC in samples 0=none       : ',I4)
314  FORMAT(' 14.  Screen (1) Metafile (0 noview) : ',I4)
315  FORMAT(' 15.  Mark first breaks (1=yes)     : ',I4)
316  FORMAT(' 16.  Normalize each trace (1=yes)   : ',I4)
317  FORMAT(' 17.  Plot the title (1=yes)      : ',I4)
318  FORMAT(' 18.  Contour display (1=yes)      : ',I4)
320  FORMAT(' 0.   FINE ! end  ')
      write(*,*)'       Enter option ... <RETURN> then input '

      read(*,*)NOPT

      IF(NOPT.EQ.0) GOTO 424
      IF(NOPT.EQ.1) GO TO 3300
      IF(NOPT.EQ.2) READ(5,* )IFTR,ILTR,inte
      IF(NOPT.EQ.3) READ(5,* )IFPO,ILPO,NZ
      IF(NOPT.EQ.4) READ(5,* )IVA
```

```
      IF(NOPT.EQ.5) READ(5,* )IPOL
      IF(NOPT.EQ.6) READ(5,* )IWIG
      IF(NOPT.EQ.7) READ(5,* )DX
      IF(NOPT.EQ.8) READ(5,* )DZ
      IF(NOPT.EQ.9) READ(5,* )IDORT
      IF(NOPT.EQ.10)READ(5,* )DEFL
      IF(NOPT.EQ.11)READ(5,* )ITRSC
      IF(NOPT.EQ.12)READ(5,* )TRSC
      IF(NOPT.EQ.13)READ(5,* )IAGC
      IF(NOPT.EQ.14)READ(5,* )IMODE
      IF(NOPT.EQ.15)READ(5,* )IFB
      IF(NOPT.EQ.16)READ(5,* )INOR
      IF(NOPT.EQ.17) THEN
      READ(5,* )ITITLE
      IF(ITITLE.EQ.1) THEN
      write(*,*)'Enter the title'
      READ(*,238),TITLE
      write(*,*) 'Is it a shot record ? (1=yes)'
      read(*,*)ISHOT
238   FORMAT(A60)
      ENDIF
      ENDIF
      IF(NOPT.EQ.18) THEN
      READ(5,* )ICONT
      IF(ICONT.EQ.1) THEN
      write(*,*),'Enter min contour level,interval & number of levels'
      read(*,*),CLASS(1),CLASS(2),NCLASS
      ENDIF
      ENDIF
      GO TO 300


3300 CONTINUE


      NTRPLT = ILTR-IFTR+1
      NSPLT = ILPO-IFPO+1
               NX=NTRPLT
      write(*,*)' NTRPLT = ',NTRPLT
      write(*,*)' NSPLT = ',NSPLT
C    ------- READ DATA FROM THE FILE ------
      IF(IJK.EQ.1) THEN
      IJK=0
      OPEN(2,FILE=FP,ACCESS='DIRECT',RECL=4*NZ,STATUS='OLD')
      DO 737 II=iftr,iltr
           kk=ii-iftr+1
           if(inte.gt.0) i4=ii
           if(inte.lt.0) i4=iltr-ii+iftr
c     READ(2,REC=II)(RDAT(JJ,kk),JJ=1,ipo)
           read(2,rec=i4)(plot(jj,kk),jj=1,ilpo)
737   CONTINUE
      END IF
      write(6,*)'out of read file'
ccccccccccccccccccccccccccccccccccccccccccccccccc
c           tshift=0
            tshift=993
            iftr=iftr+tshift
            iltr=iltr+tshift
ccccccccccccccccccccccccccccccccccccccccccccccccc
747         continue

      IF(IAGC.GT.0)THEN
           CALL AGC(ilpo,NSPLT,NX,PLOT,IAGC)
      ENDIF
           CALL GBEGIN('Select mx11;exit','dollop',PLOT)

C   Plot size, normalize if required

      XMAX = 0.0
      DO 700 J =1,nx
      XMTR = 0.0
      DO 701 I = IFPO,ILPO
      TRACE(I) = PLOT(I,J)
701   CONTINUE
      CALL MAXSN(ILPO,TRACE,XX,JI)
      IF(XX.GT.XMAX)XMAX = XX
      IF(INOR.EQ.1)THEN
           if(xx.eq.0.)xx=1.0
           DO 1053 I = 1,ilpo
           PLOT(I,J) = PLOT(I,J) /xx
1053     CONTINUE
      ENDIF
700   CONTINUE

      IF(INOR.EQ.1)XMAX = 1.0

      IF(IDORT.NE.1) DZ=DZ/1000.0
      RESERV = 40.0

      CALL GRPSIZ(XSIZE,ZSIZE)


      ONEMMY = 1.0
      ONEMMX = 1.0
ccccccccccccccccccccccccccccccccccccccccccccccccc
      XOR = RESERV
      ZOR = ZSIZE - RESERV
      SAMPMM = (ZSIZE-2*RESERV)/(NSPLT-1)
      IF(NTRPLT.EQ.1)THEN
      TRACMM = (XSIZE-3*RESERV)
      ELSE
      TRACMM = (XSIZE-2*RESERV)/(NTRPLT-1)
c              TRACMM=1.0
      ENDIF


      IF(ICONT.EQ.1) THEN
      RESERV = 20.0
      ONEMMX = 1/(XSIZE - 3*RESERV)
      ONEMMY = 1/(ZSIZE - 2*RESERV)
      XOR = 0.0
      ZOR = 1.0
      SAMPMM = 1/(NSPLT-1)
      TRACMM = 1/(NTRPLT-1)
      CALL GVPORT(2*RESERV,RESERV,XSIZE-3*RESERV,ZSIZE-2*RESERV)
      CALL GWBOX(XSIZE-3*RESERV,ZSIZE-2*RESERV,0.0)
      CALL GLIMIT(0.0,1.0,0.0,1.0,0.0,0.0,0.0)
      CALL GSCALE

C   Set up the colour
```

```
      CALL RSHADE(1,0)
      CALL RCLASS(CLASS,NCLASS,5)
      ENDIF

      IF(ITRSC.EQ.1)THEN
      XSIZE = (NTRPLT-1)*DX*TRSC
      IF(NTRPLT.EQ.1)XSIZE = DX*TRSC
      ZSIZE = (NSPLT-1)*DZ*TRSC
      ENDIF

      TRACD = XMAX / DEFL
      CALL SSMPSI(TRACMM,SAMPMM,TRACD)
      PRINT*, 'XMAX = ', XMAX
      CALL SORIG(XOR,ZOR)
      CALL SNUMBS(+1)
      CALL SNUMBD(5.0*ONEMMY)
      CALL SNUMBJ(1)
      CALL SNTRAC(NTRPLT)
      CALL SDIR(+1,-1)

C   Polarity etc

      NEGPOS = 1
      IF(IVA.EQ.1)THEN
           KTYPE=0
      ELSE
           KTYPE=1
      ENDIF
      IF(IWIG.EQ.1)THEN
           KSLINE = 0
      ELSE
           KSLINE = 1
      ENDIF

      CALL STYPEW(KTYPE,NEGPOS,KSLINE)

      IF(IPOL.EQ.1)THEN
           RPOL = 1.0
      ELSE
           RPOL = -1.0
      ENDIF

      CALL SWICOL(0.05,1)
      CALL SNUMBH(4.5)

      NMBTR = IFTR
      DO 1000 J = 1,nx
           DO 2000 I = IFPO,ILPO
                TRACE(I-IFPO+1) = PLOT(I,J) * RPOL
2000     CONTINUE

      IF(ICONT.EQ.1)CALL SCOLC(TRACE,NSPLT)
      IF(ICONT.NE.1)CALL SWIGG(TRACE,NSPLT)

      IF(J+iftr-1.EQ.IFTR)CALL SRORIG(XX,YY,XE,YE)
C      XO YO ARE ORIGIN OF FIRST TRACE
      IF(J+iftr-1.EQ.NMBTR)THEN
                CALL SRORIG(XO,YO,XE,YE)
                CALL SNUMBJ(1)
                CALL STRNMB(J+iftr-1)

                POSX(1) = XO
                POSY(1) = YO + 1*ONEMMY
                POSX(2)= XO
                POSY(2) = YO + 4*ONEMMY
                CALL GVECT(POSX,POSY,2)
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
                NMBTR = NMBTR+50
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C          Number every fifty traces
      ENDIF
1000 CONTINUE



C   first anno val
C   delta anot
C   no sams between annot
C   no decimal places
      X1 = (IFPO-1)*DZ
      X3 = 200
      IF(NSPLT.LE.1024)X3 = 100.0
      IF(NSPLT.LE.512) X3 = 100.0
      IF(NSPLT.LE.256) X3 = 20.0
      IF(NSPLT.LE.128) X3 = 10.0
      IF(NSPLT.LE.56)  X3 = 5.0
      IF(ICONT.NE.1) THEN
      X4 = X3*DZ
      CALL SNUMBS(2)
      CALL STIMEE(5.0,5.0)
      CALL SNUMBD(2.0)
      CALL SNUMBH(3.5)
      CALL STIMLJ(X1,X4,X3,1)

      ENDIF

      CALL SWICOL(0.2,1)
      IF(IFB.EQ.1)THEN
C          Mark fb with dot and colour trace upto fb
           CALL SWICOL(1.0,3)
           CALL GWICOL(0.8,1)
           CALL SORIG(XX,YY)
C          Set the same origin
           DO 1500 J = 1,nx
                CALL ZERO(2048,TRACE)
                DO 2500 I = IFPO,NFIRST(J)
                     TRACE(I-IFPO+1) = PLOT(I,J) * RPOL

2500           CONTINUE
                CALL SWIGG(TRACE,NFIRST(J)-IFPO)
C               Colour trace to one sample BEFORE fb
                CALL SRORIG(XD,YD,XFB,YFB)
                CALL GDOT(XFB,YFB,1)
1500       CONTINUE
      ENDIF

      RBCE=15.0
      IF(ICONT.EQ.1) THEN
      CALL SNUMBS(1)
      CALL SNUMBD(2*ONEMMX)
      CALL STIMEE(5*ONEMMX,5*ONEMMX)
```

```
        CALL STIMLI(X1,X3*DZ,X3,1)                          END
        CALL GSCAMM                                 C
        CALL GCOSCS(5.0,RESERV)                             SUBROUTINE ZERO(LX,X)
        RBCE = RESERV+6.0                                   IMPLICIT REAL (A-H,O-Z)
        ENDIF                                               DIMENSION X(LX)
                                                    C
        CALL RTXHEI(4.5)                                    IF(LX.LE.0)RETURN
        CALL RTXJUS(1,2)                             C
        CALL RTXPAT(0)                                      DO 10 I=1,LX
        CALL RTXFON('COMP',0)                       10     X(I)=0.0E0
        IF(ISHOT.NE.1) THEN                          C
                                                            RETURN
cccccccccccccccccccccccccccccccccccccccccccccccccc          END
        CALL RTX(-1,'CDP #',RESERV-20,ZSIZE-RESERV+6)
cccccccccccccccccccccccccccccccccccccccccccccccccc
                                                            SUBROUTINE AGC(N,NSAMR,NRECS,X,LEN)
        ELSE                                        C   c/o MF
        CALL RTX(-1,'CHANNEL #',RESERV-20,ZSIZE-RESERV+6)   REAL X(N,NRECS),XPRIME(1024)
        ENDIF                                               DO 100 J = 1, NRECS
        CALL RTXSPM(1)                                        CALL ZERO(NSAMR,XPRIME)
        CALL RTXJUS(1,2)                                      DO 50 ICEN = 1, NSAMR
        CALL RTXPAT(3)                                          L0 = LEN
        CALL RTX(-1,'TIME IN MSECS',RECE,0.5*ZSIZE)            IF(ICEN .LE. LEN/2) L0 = 2*ICEN - 1
                                                               IF(ICEN .GT. NSAMR-LEN/2) L0 = (NSAMR-ICEN+1)*2 - 1
        IF (ITITLE.EQ.1) THEN                                  CALL RMSERR(L0,X(ICEN-L0/2,J),RMS)
        CALL RTXJUS(1,1)                                       IF(RMS .EQ. 0.0) GO TO 50
        CALL RTXSPM(0)                                         XPRIME(ICEN) = X(ICEN,J) / RMS
        CALL RTXPAT(0)                               50     CONTINUE
        CALL RTXFON('ITAL',0)                                 DO 75 I = 1, NSAMR
        CALL RTXHEI(4.5)                                        X(I,J) = XPRIME(I)
        CALL RTX(-1,TITLE,XSIZE/1.8+10,28.0)        75     CONTINUE
        ENDIF                                       100 CONTINUE
                                                            RETURN
        CALL GEND                                           END
cc      CALL GCLOSE
        IF(IDORT.NE.1) DZ=DZ*1000.0
                                                            SUBROUTINE RMSERR(NSAMR,X,RMS)
424     CLOSE(2)                                            REAL X(NSAMR)
        STOP                                                RMS = 0.0
        END                                                 DO 10 I = 1, NSAMR
                                                              RMS = RMS + X(I)**2
                                                    10 CONTINUE
                                                            RMS = RMS / NSAMR
        SUBROUTINE MAXSN(LX,X,XM,II)                        RMS = SQRT(RMS)
        IMPLICIT REAL (A-H,O-Z)
        DIMENSION X(LX)                                     RETURN
C                                                           END
        II=1
        DO 10 I=1,LX
10      IF(abs(x(ii)).lt.abs(x(i))) ii=i
        XM=abs(X(II))
C
        RETURN
```