Estimation of Near Surface effects; an alternative approach to statics

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3.1 Introduction

In DELPHI Volume IV, Chapter 3 (1993) it was argued that by making assumptions about the propagation behavior of a synthesized (plane) wave through a weathered layer it is possible to consider the weathered layer effects at the source and receiver side separately. The fast weathered layer distortion to the (plane) wave front at the source side is largely restored during propagation through the medium (far field). For the upgoing wave field this restoration does not occur because the receivers measure the distorted wave field in the near field of the weathered layer. Starting with these assumptions an estimate of the weathered layer interface can be made. In this Chapter this estimate is obtained in an iterative way and used to make a correction to the weathered layer influence at the receiver side. The procedure can be repeated at the source side (reciprocity). At the end of this Chapter a proposal is made to include the weathered layer problem in macro model estimation.

3.2 Iterative estimation of the weathered layer interface

A wave emitted by a source at the surface propagates down, gets reflected from deeper interfaces and propagates back to the receivers at the surface. If there is a weathered layer at the surface then the wave field travels at least two times through the weathered layer: the first time

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when it is emitted by the source and the second time just before it is recorded at the surface. The upgoing wave field which arrives at the surface contains all the structural information of the subsurface where it has travelled through. When the upgoing wave field is recorded in the presence of a weathered layer all the information of the subsurface is distorted in a consistent way due to the irregular weathered layer.

By using synthesized downgoing plane waves at the surface it is possible to estimate from the recorded upgoing wave field at the surface the propagation effects of the weathered layer. It is then assumed that the detailed weathered layer disturbances originating at the source position have been largely restored in the far field ("healing effect"). So the detailed part of the propagation information of the weathered layer can be extracted from the upgoing wave field at the receivers (near field effects).

To arrive at an initial estimation of the weathered layer interface the following two assumptions are made:

- restoration of the disturbances in the downgoing wave field occurs due to *fast* lateral changes in the weathering,
- a given estimate of the upgoing wave field is available just below the weathered layer at the receiver side.

In DELPHI Volume IV, Chapter 3 (1993) it was shown that with these assumptions it is possible to make an estimate of the weathered layer. In this section three examples are given to show the potential of the method; one example is given to show the convergence of the iterative approach, in the second example the influence of an improper assumption of the upgoing wave field is considered and in the third experiment the influence of residual distortion of the source wave field is evaluated.

In Figure 3.1 the iterative estimation procedure is schematically given. The input wave field $\vec{P}^-(z_0)$ of the iteration scheme is a synthesized shot record (Rietveld, 1992). The synthesis operator can be a simple addition of the common receiver gather for all shots, which means synthesis for a plane wave at the surface. Hence, in this case $\vec{P}^-(z_0)$ can be interpreted as the upgoing response at z_0 due to a downgoing plane wave at z_0. Illumination by more than one plane wave will give more additional propagation information of the weathered layer.

In the initialization procedure (Figure 3.1) a homogeneous model is defined with an estimated velocity of the weathered layer $\bar{c}_1$ and an initial coarse depth variation of the weathered layer interface $\bar{z}_1$. The initial depth variation and the estimated velocity of the weathered layer can be obtained by local geological knowledge or measurements in the field. Note that we may have $\bar{z}_1 = \bar{z}_1(x, y)$ and $\bar{c}_1 = \bar{c}_1(x, y)$. After extrapolation to a reference depth level z_r just below the weathered layer the extrapolated field $\vec{P}_e^-(z_r)$ is compared with an upgoing wave field $\vec{P}^-(z_r)$ at z_r. If both wave fields are equal to each other the iteration stops. If there is a mismatch the model is updated.

The actual upgoing wavefield below the weathered layer can be calculated by inverting the relation

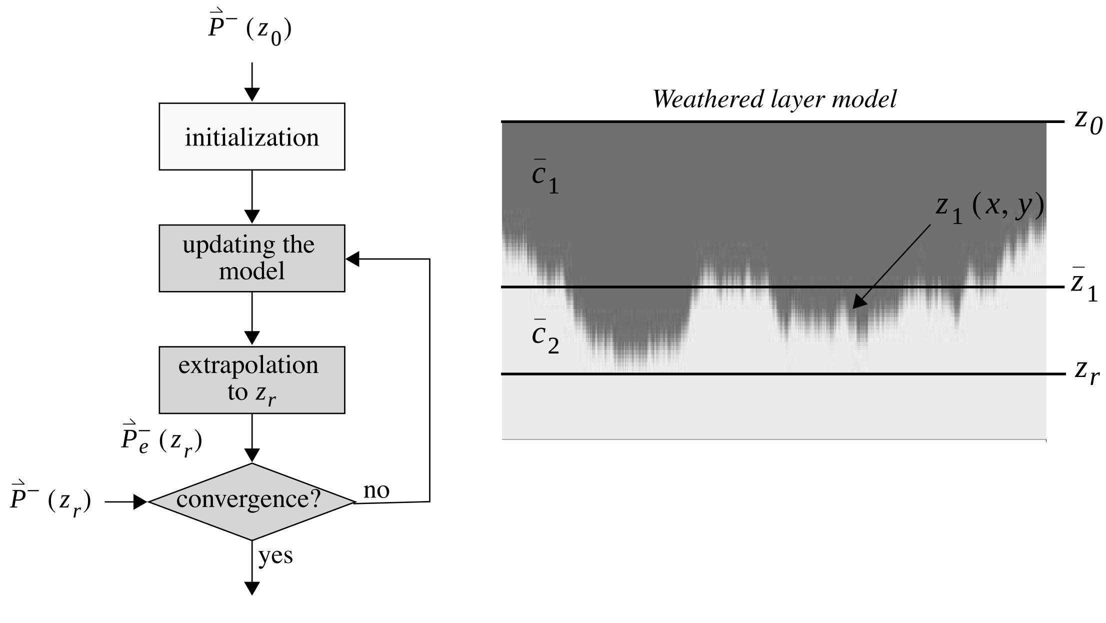


Figure 3.1: *Iterative estimation procedure and a schematic model of a weathered layer.*

$$\vec{P}^-(z_0) = \boldsymbol{W}^-(z_0, z_r)\vec{P}^-(z_r) . \tag{3.1}$$

In Equation (3.1) there are two unknowns; the upgoing propagation matrix $\boldsymbol{W}^-$ through the weathered layer and the actual upgoing wave field $\vec{P}^-(z_r)$ at reference depth level z_r. In order to solve this equation we make an assumption for the upgoing wavefield at z_r. With this assumption we can solve the equation and make a first estimation of the propagation model of the weathered layer. If there is information available of the macro model the assumption of the upgoing wave field at z_r can be updated according to

$$\vec{P}^-(z_r) = \boldsymbol{W}^-(z_r, z_m)\boldsymbol{R}^+(z_m)\boldsymbol{W}^+(z_m, z_0)\vec{S}^+(z_0) \tag{3.2}$$

with $z_m = z_m(x,y)$. Preferably different macro boundaries are used. The propagation matrices in Equation (3.2) are determined by the known macro model. In this chapter we will start by assuming knowledge of the upgoing (plane) wavefield $\vec{P}^-(z_r)$ in order to make an estimation of the propagation model of the weathered layer. At the end of this chapter the macro model will be included in the estimation technique.

The mismatch between the assumed upgoing wave field $\vec{P}^-(z_r)$ and the extrapolated result $\vec{P}_e^-(z_r)$ is expressed in a time difference for every trace. The time differences are calculated with a cross correlation (or deconvolution) between the extrapolated result and the assumed upgoing wave field. Tracking the crosscorrelation information gives a time difference for every trace. This picked cross section with time differences is converted to depth by using the estimated weathered layer velocity. Substraction of the mean from this depth trace gives an estimation of the *shape* of the interface. This estimated interface is placed at the estimated average depth of the weathered layer. If the estimated depth or velocity is wrong the estimated weathered layer model will also be wrong but the assumed upgoing wave field at z_r will come out correctly (we will come back to this later).

3.2.1 First example; convergence of the iteration

The described iterative procedure is explained with a simple example in which an upgoing plane wave is placed below the weathered layer and receivers are placed above the weathered layer (see Figure 3.2). In this example the distance between the receivers is 2 m and the time interval in the recording is 2 ms. The model is 1100 m wide and the plane wave field is defined at 140 m depth. The velocities of the layers above and below the weathered layer are 600 m/s and 1800 m/s respectively. The interface is modelled with a vertical velocity gradient of 60 m/s over a depth of 20 meter. The assumption about the restoration is not necessary in this example and if we choose for the upgoing wave field $\vec{P}^-(z_r)$ at reference depth z_r a plane wave, then both assumptions stated before are correct. So with this ideal experiment the convergence of the iterative procedure can be tested.

From the registration in Figure 3.2 we see that the plane wave is significantly distorted due to the irregularities in the weathered layer interface; diffraction curves are also present in the recording. They contain information on the irregularities of the weathering. Correcting the dis-

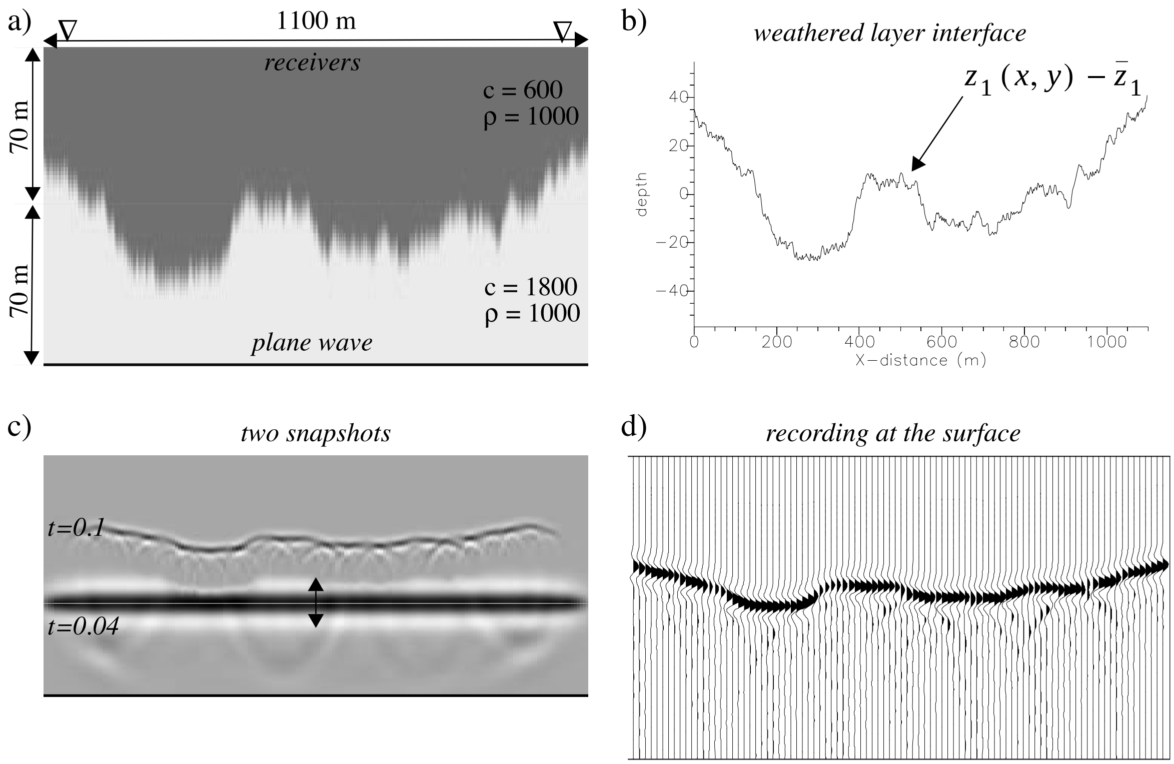


Figure 3.2: *a) Model description and registration at the surface for a simple model to test the iteration process.*
b) the weathered layer interface around the average depth as function of x.
c) snapshot at two times shows that the wavelength in the weathered layer is very small due to the low velocity. In both c) and d) diffraction curves can be observed, due to the fast lateral changes.

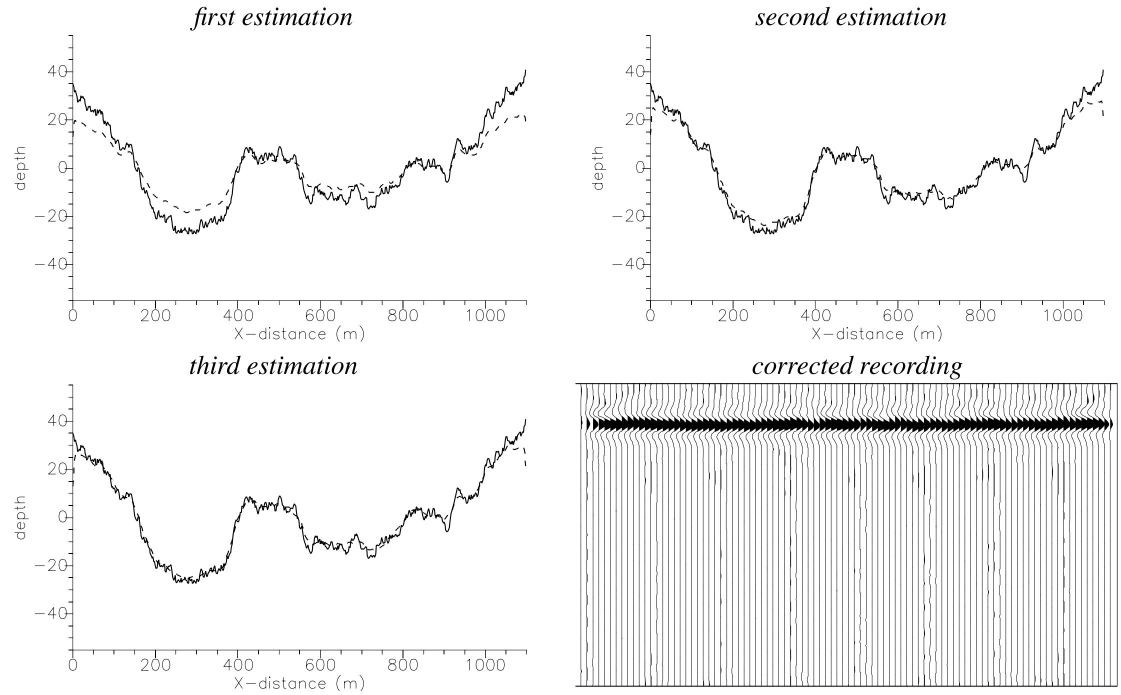


Figure 3.3: *Estimated interface for one, two and three iterations and the corrected shot record after three iterations. The dotted line represents the estimation, the solid line represents the shape of the true interface. The recorded upgoing wavefield at z_r is indeed a plane wave.*

torted plane wave with a time shift only yields a plane wave with incorrect amplitudes and uncorrected diffraction curves. The method proposed in Figure 3.1 is based on the wave equation and should focus the diffraction energy to their correct position when the correct velocity and depth is used.

In the estimation the initial velocity and depth of the model are respectively taken at 600 m/s and 60 m. The first, second and third estimation of the weathered layer interface are shown in Figure 3.3. The solid line in Figure 3.3 represents the true interface used in the synthetic model, the dotted lines represent the estimated interface after the successive iteration steps. The first estimation of the interface shows a depth variation which is not correct for all positions. The second estimation gives already a good estimation of the interface. The third estimation shows that the iterative procedure does not overcorrect the estimated result, but converges to the correct answer. The estimated interface is a ‘smoothed’ version of the true interface due to the limited resolution in the seismic experiment. The corrected shot record is also shown in Figure 3.3. The result resembles the assumed upgoing wave field below the weathered layer, which was a horizontal plane wave. Note that in the corrected result the energy of the diffraction curves present in Figure 3.2 are focussed to their correct position in Figure 3.3.

3.2.2 Second example; influence of errors in the upgoing wave field $\vec{P}^{-}(z_r)$

How structure interferes with the estimation of the weathered layer is explained in an example with three exploding reflectors; two dipping reflectors and one flat reflector. In this experiment

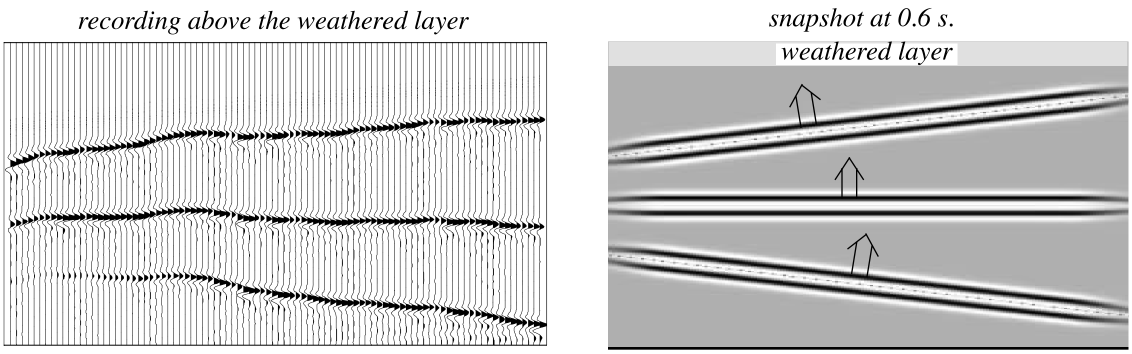


Figure 3.4: *Model with three exploding reflectors below the weathered layer. In the left picture the recording above the weathered layer is shown, the right picture shows a snapshot. Note the irregular shape of the waves in the recording above the weathered layer.*

the assumption about the upgoing wave field $\vec{P}^-(z_r)$ below the weathered layer interface will be tested. By assuming for every event an upgoing plane wave below the weathered layer the structure of the upgoing dipping plane waves must, in some way, be present in the estimation of the weathered layer. In this experiment the modeling parameters are the same as in the previous experiment. The model is extended in the z direction to position the exploding reflectors properly. The time step in the recording is chosen at 4 ms. The recording and a snapshot are shown in Figure 3.4. The exploding reflectors have, from top to bottom, a dip of respectively -15, 0 and 15 degrees, which can be observed in the snapshot. The recording shows three disturbed plane waves. The event at the bottom is at the left side decaying in amplitude because of the limited length of the source array in the synthetic model.

For a first estimation of the weathered layer interface the first recorded event is selected (by muting out the other two). A second and third estimation of the weathered layer interface are obtained by selecting the second and third event. The selected event is the input file for the iterative estimation scheme. For every event we will assume an upgoing horizontal plane wave below the weathered layer and use the correct velocity of the weathered layer. Note that this assumption is only correct for the middle event. The results obtained with this assumption for the three events is shown in Figure 3.5b, c and d. In Figure 3.5a the true interface is shown. The first and third estimation of the weathered layer are distorted by the dip of the incoming plane wave. The second estimation comes out correctly and resembles the true interface. This example shows that the estimation result depends on the difference between the assumed upgoing wave field and the actual wave field. The obtained estimation can thus be interpreted as an effective propagation model with respect to the assumed upgoing wave field. If there is no knowledge about the shape of the upgoing wave field then it is not possible to determine which estimation is correct.

For every other assumed upgoing wave field and every other reflector another propagation model of the weathered layer can be estimated. Combining the different estimations can give some insight in the subsurface structures present in the estimation if there is information avail-

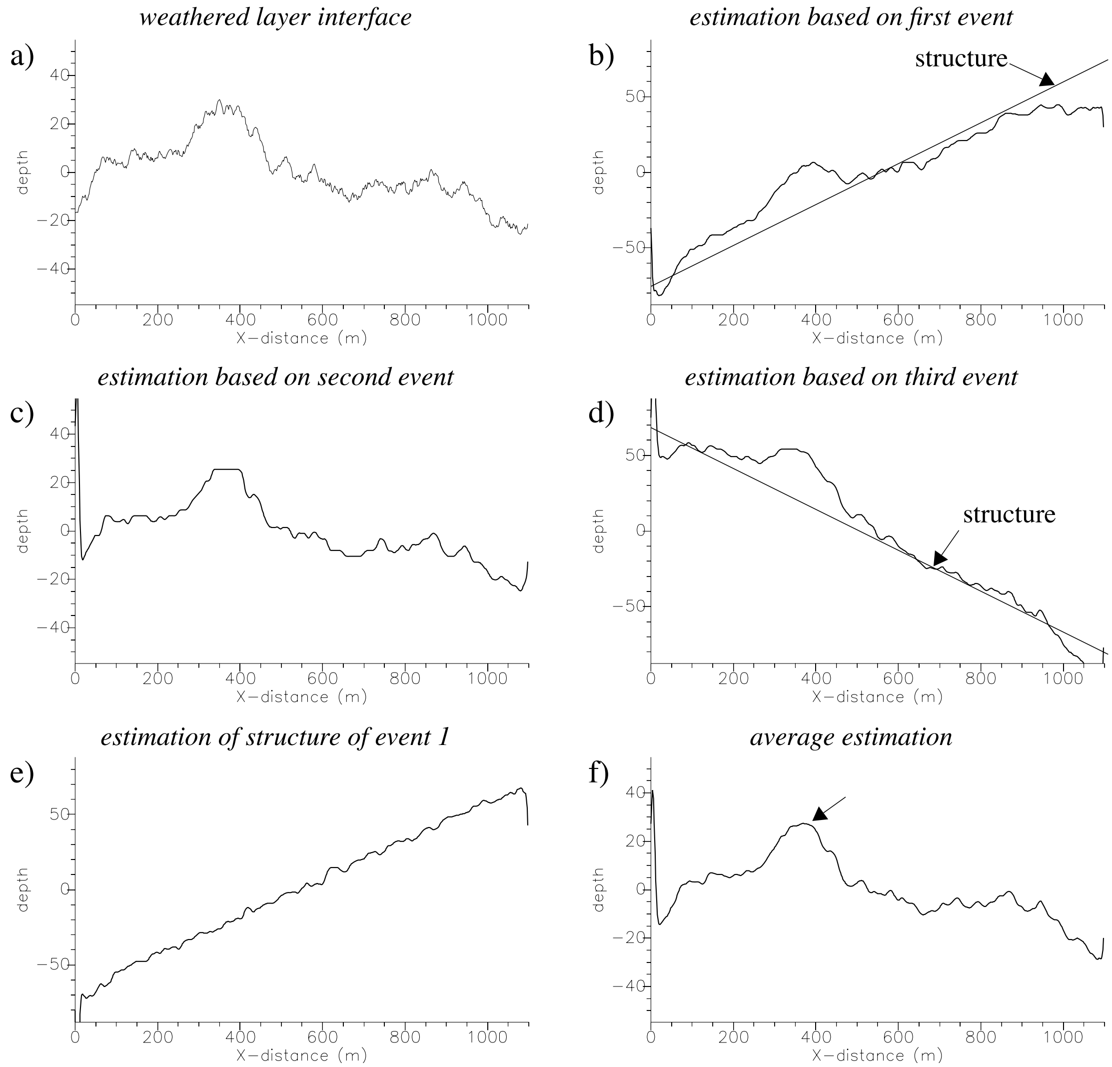


Figure 3.5: *a) The weathered layer interface used in the exploding reflector model.*
b) Estimated interface based on the exploding reflector of -15 degrees.
c) Estimated interface based on the exploding reflector of 0 degrees.
d) Estimated interface based on the exploding reflector of 15 degrees.
e) Estimation of the structure of event 1 by subtracting c) from b).
f) Average estimation of the weathered layer interface by averaging b), c) and d).

able about the structure present in one single event. For example, if we assume nearly vertical propagation through the weathered layer then we will get an estimation of the structure of the first reflector by subtracting the estimation of the second event, which structure we assume we know (a horizontal plane wave), from the first see Figure 3.5e. The same information can be obtained by taking the cross-correlation (or deconvolution) between the selected events. The crosscorrelation result will show the difference in structure between the selected events.

In the chosen exploding reflector example it is also possible to combine the three estimations into a final one by taking the average of the three estimations if we assume that the average dip is zero (which is true in this case). The result is shown in Figure 3.5f. The difference between the estimation based on the second event (Figure 3.5c) and the averaged estimation is that the average estimation contains also propagation information for higher angles of incidence. This is observed in the area indicated by the arrow.

3.2.3 Third example; influence of imperfect restoration of the plane source wave field

As a last example a plane wave shot record response for a model with one reflector is modelled. In this example the assumption about the restoration of the source wave field can be tested. Starting with a horizontal plane source at the surface the downgoing wave field propagates through the weathered layer at the surface down into the subsurface. At the reflector most of the weathered layer disturbances will be restored due to propagation (which was shown in the previous DELPHI Volume). After reflection part of the wave field travels back to the surface and propagates for the second time through the weathered layer. At the surface the reflection is measured by the receivers. The shot record with the reflection and the model for this experiment are shown in the top of Figure 3.6. The contrast between the velocities of the weathered layer and the layer below is taken less than in the previous two examples. In the estimation process the correct velocity is used and an upgoing plane wave is assumed below the weathered layer.

The true shape of the interface and the estimated shape are shown in the bottom of Figure 3.6. The corrected reflector response at depth level z_r is also shown. The estimation of the interface is in the steepest parts too big. This offset in the estimation is due to the fact that the wavefield

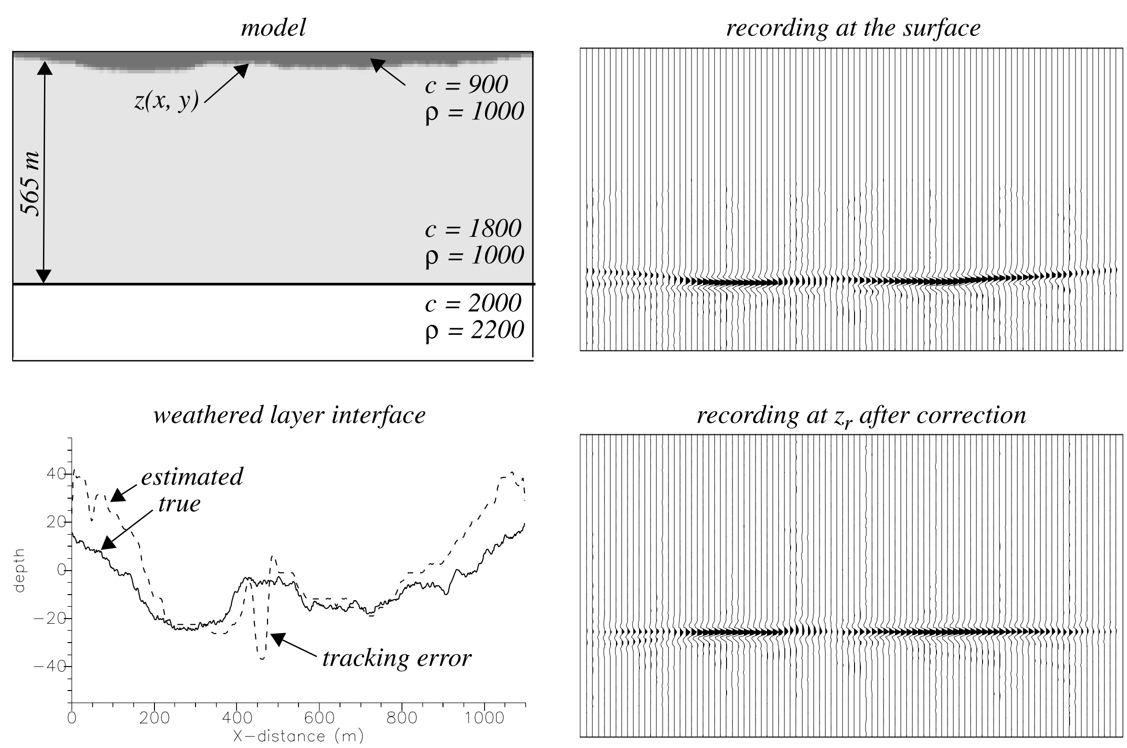


__Figure 3.6:__ Model with one deep reflector and a weathered layer at the top. At the right the recording at the surface (top) and the recording below the weathered layer (bottom) are shown. The inverse extrapolated upgoing wave field at z_r is indeed the (wrongly) assumed plane wave. Note the tracking error in the estimation.

below the weathered layer is not exactly the assumed horizontal plane wave. The actual upgoing wave field at z_r contains all the propagation effects of the reflected source wave field, thus it contains also the trend of the weathering. The assumed upgoing flat plane wave field comes out correctly. Due to a discontinuity in the reflection a tracking error is visible in the estimation (indicated by the arrow). This discontinuity is also visible in the corrected result. With the aid of the estimated weathered layer model a new guess about the upgoing wave below the weathered layer can be made by taking the propagation effects of the weathered layer into account. In section 3.4 we will come back to this problem.

3.3 Sensitivity to errors

The three examples given in the previous section are all synthetic examples and give excellent results, but how are these results influenced when we use wrong input parameters for the estimation technique? To get some insight in the robustness of the estimation technique some experiments are carried out. The same model as in the first example is used again. The estimation is carried out with several velocities for the weathered layer. The results of these experiments are shown in Figure 3.7a for two different velocities. An error in the velocity of the weathered layer gives different estimations of the interface. A velocity which is too low gives an interface which has smaller variations than the true interface. An error in the velocity of the layer below the weathered layer does not have much influence on the estimated shape of the interface, see Figure 3.7b. An error in the average depth of the weathered layer interface does not influence the estimated result either.

The estimation technique is directly dependent on a good tracking algorithm. If the lateral continuity of the reflection is worse the method will fail to track the cross correlated record correctly and the estimated interface will be wrong. The iterative procedure cannot update for these tracking errors. In that case the reference depth level below the weathered layer (z_r) is also of importance. If the estimation is not correct and the depth level is chosen too far below the weathered layer then the errors made in the estimation will propagate more pronounced to z_r.

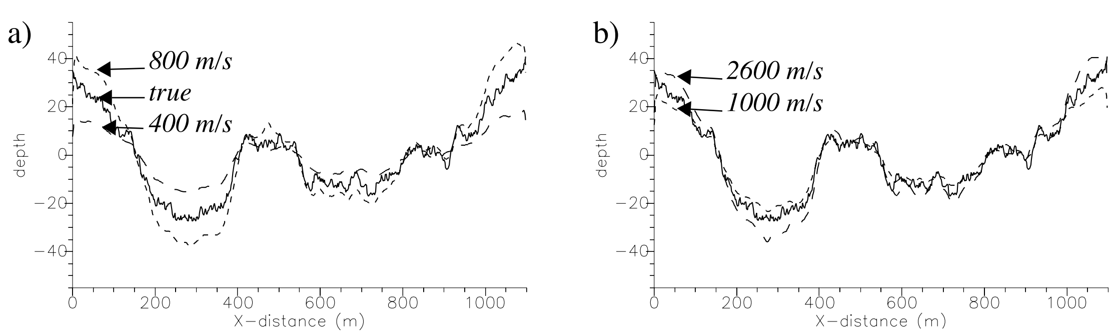
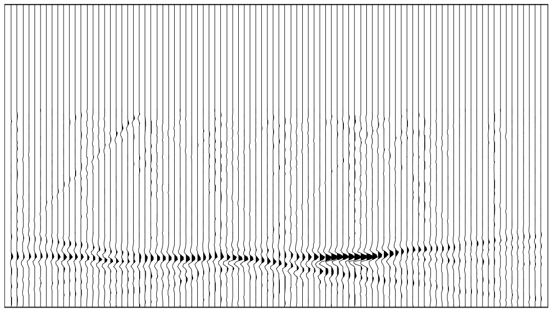


Figure 3.7: *Sensitivity to velocity errors.*
a) Velocity error in the velocity of the weathered layer have an influence on the estimate.
b) Velocity error in the velocity of the layer below the weathered layer don't have much influence



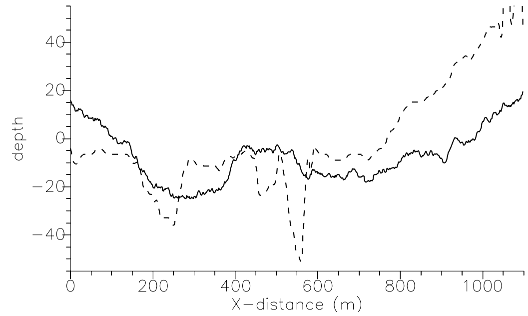


Figure 3.8: *A lateral discontinuity of the reflection leads to tracking errors and a wrong estimation.*

An example of a tracking error is obtained by using a big contrast between the weathered layer and the layer below in the reflector model (third example in the previous section with the velocity of the weathered layer at 600 m/s). Given a big contrast the downgoing plane wave below the weathered layer gets discontinuous due to the great time differences between the different parts of the plane wave. The event to be tracked consists in this case of a discontinuous plane wave as shown in Figure 3.8, so the tracking algorithm can easily follow the wrong event. The estimated interface based on this reflector is totally wrong due to this tracking error.

3.4 Integration with macro model estimation

The examples in the previous sections showed that knowledge of $\vec{P}^-(z_r)$ is required in order to make a correct estimation of the weathered layer. In this section a method will be discussed that estimates the upgoing wave field at reference depth z_r; this result will be used to correct the weathered layer estimation.

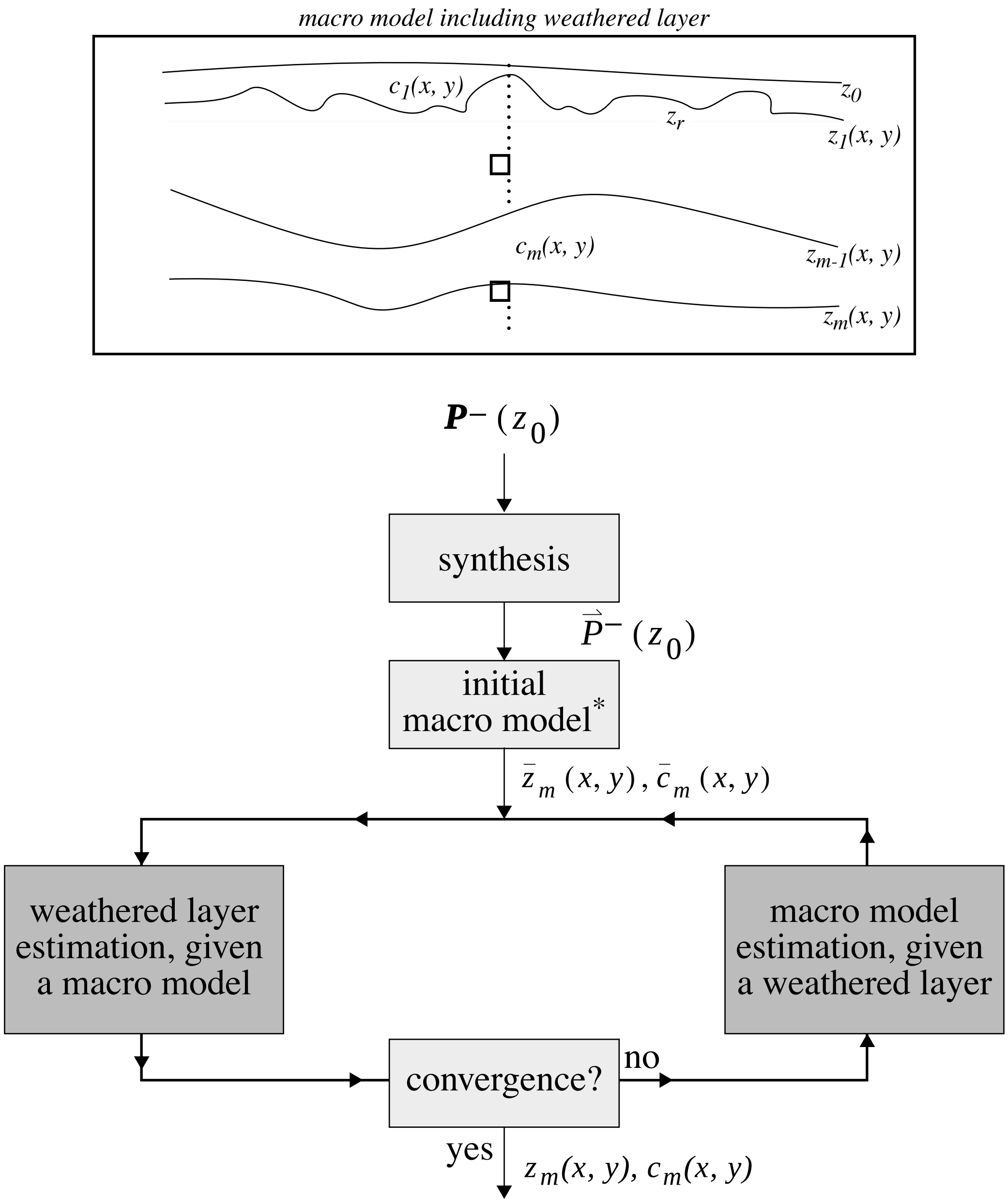
Naturally the weathered layer estimation should be a first step in a macro model estimation. From the result shown in the section 3.2, example 2 we have seen that it is impossible to make a good estimation of the weathered layer if we cannot discriminate between the structure in the macro model and the weathered layer effects. The most convenient way to solve this problem is to develop a scheme which, in an iterative way, estimates the weathered layer combined with the macro model estimation. The obtained macro model will then be more detailed close to the surface due to the special treatment of the weathered layer.

In Figure 3.9 a flow diagram is given for an estimation technique in which the weathered layer is given special attention. The synthesis process in the scheme is defined for a plane wave at the surface, which is a simple summation of the common receiver gathers over all shots. The weathered layer estimation technique is the one given in Figure 3.1. In the diagram in Figure 3.1 the assumed upgoing wave field at depth z_r, $\vec{P}^-(z_r)$, is the plane wave response at z_r defined by the estimated macro model, so

$$\vec{P}^-(z_r) = \boldsymbol{W}^-(z_r, z_m)\,\boldsymbol{R}^+(z_m)\,\boldsymbol{W}^+(z_m, z_0)\,\vec{S}^+(z_0)\,, \tag{3.3}$$

where the propagating matrices $\boldsymbol{W}$ are defined by the macro model.

The estimation will stop if the correction for the weathered layer is sufficient small. The whole estimation procedure is reflector dependent so the procedure starts with the reflector which is nearest to the surface and will work downward towards deeper reflectors. In this way for every reflector an estimation of the weathered layer interface is made and if the macro model is correct these estimations should be similar. If the estimates are not similar then the estimated



*) including initial estimate of weathering (e.g. with conventional statics technology)

Figure 3.9: *Macro model estimation combined with weathered layer estimation.*

macro model is wrong and should be updated. The macro boundaries can be detected by using a median filter in the synthesis process, see Chapter 11 in this Volume.

For example let us assume a model with only one flat reflector in the subsurface $z_2(x, y) = z$, and at the surface an irregular shaped weathered layer described by $z_1(x, y)$ and $c_1(x, y)$. The upgoing wavefield below the weathered layer will be a plane wave disturbed with the propagation effects due to the weathered layer effects at the source side. If the restoration at the source side is not complete and the initial macro model is not correct then the upgoing plane wave contains some residual trend of the weathering. As a first estimation of the wavefield at a defined horizontal reference level z_r below $z_1(x, y)$ an upgoing plane wave is assumed in the left branch of Figure 3.9. Based on this assumption a first estimation of the weathered layer is made. In the third example in the previous section it was already shown that this estimation was not correct, because the upgoing plane wave still contains trend information of the weathering. In the proposed method the upgoing wave field at a horizontal level below $z_1(x, y)$ can be calculated again with the updated macro model, which is represented by the right branch in Figure 3.9. Based on this new macro model an updated upgoing wave field at z_r can be calculated and a new estimation of the weathered layer can be made. If the correction in the weathered layer estimation is still too large the macro model updating will start again. After a few updating steps the weathered layer interface will be estimated correctly. If there are non-flat reflectors in the subsurface we have to correct for this as well. How this correction can be done together with the macro model estimation depends on the macro model estimation technique. With the new

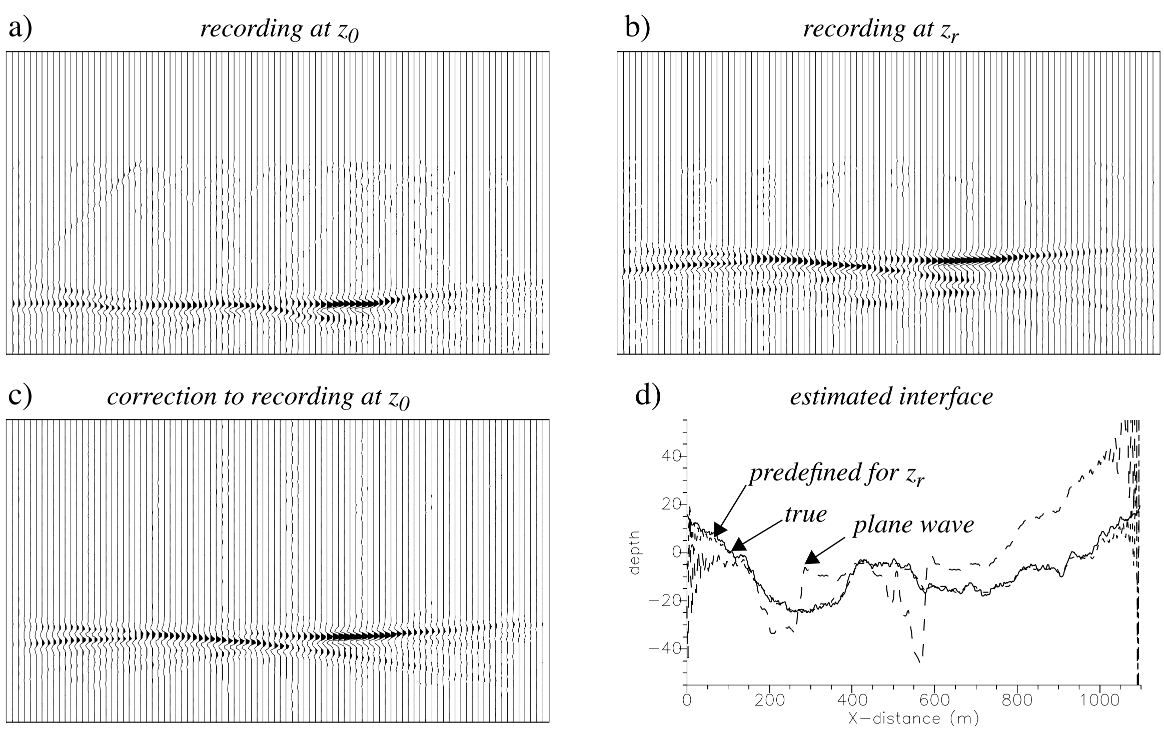


Figure 3.10: *Surface recording (a) and the recording of the upgoing wave field at z_r (b) in the reflector experiment of Figure 3.6. c) shows the corrected recording and d) the estimation of the interface with the actual wavefield at z_r and a plane wave at z_r. Note the good estimate with the correct wave field.*

technique proposed in Chapter 10 of this Volume we will try to include the weathered layer estimation technique proposed in this Chapter.

To illustrate that the method is sound, the reflector model from section 3.2, example 3 can be used again. In this experiment we change the velocity in the weathered layer to 600 m/s, which will give rise to severe tracking errors when a plane wave is assumed as upgoing wave field at z_r as shown in section 3.3. Two receiver array are positioned in the model; one at the surface above the weathered layer and one below the weathered layer at reference depth level z_r.

If we take instead of a horizontal plane wave as upgoing wave field the recording of the wave field at z_r $\vec{P}^-(z_r)$ then the weathered layer interface should come out correctly. In the estimation the correct velocity for the weathered layer is used. In Figure 3.10a and b the recording at z_0 and z_1 are shown. The estimation of the interface with the true upgoing wave field in Figure 3.10d is good and resembles the true interface and is much better than the estimation obtained with the upgoing plane wave assumption. The corrected recording at z_0 is shown in Figure 3.10c and resembles the recording of the actual upgoing wave field at z_r very good. Note that due to instabilities in the used deconvolution the edges of the interface are estimated wrong.

3.5 Conclusions and future plans

Given an upgoing wave field below the weathered layer it is possible to estimate the weathered layer interface in an iterative way. The obtained estimation contains influences of propagation effects in the subsurface and the initial source wave field. It is possible to correct for these influences by integrating the weathered layer estimation technique with a macro model estimation technique. For every macro boundary an estimation of the weathered layer interface can be made. This estimation could be repeated for several areal sources.

This proposed estimation method can be used in combination with any macro model estimation technique. In the DELPHI project we will use this method in combination with the macro model estimation technique proposed in Chapter 10.

3.6 References

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