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Iterative Pre-Stack Depth Migration With Velocity Analysis

RUEY-CHYUAN SHIH [1] and WEN-CHI CHEN[1]

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ABSTRACT

Migration image critically depends on the chosen velocity model. In principle, correct velocities are needed to obtain a correct migration image; however, such a priori knowledge of accurate velocity distributions are not always possible. In this case, a reliable velocity analysis technique is definitely needed to avoid improper data interpretation. Post-migration common-depth gather provides an excellent domain for controlling migration velocity. Examining the migrated data collected at the same depth point from different shot records, it may be underrstood if the initial velocities were correct and how best to approach a correct migration image. By incorporating the migrated common-depth gather with the pre-stack layer-stripping reverse-time migration technique, an iterative pre-stack depth migration scheme has been successfully developed with velocity analysis. The proposed algorithm analyzes migrated data iteratively until the accurate velocities are achieved. Once the correct velocity is obtained, the bottom of the migration layer may also be determined. This method allows the user some quantitative control over the final migration image. In this paper, the authors illustrate the success of the iterative velocity analysis method by using synthetic data. Field data applications are discussed elsewhere.

(Key words: Migration, Velocity analysis, Migrated common-depth gather)

1. INTRODUCTION

Seismic data recorded at the earth's surface contain seismic waves reflected from all possible directions in the earth's subsurface. Thus, the recorded seismic signals generally do not represent geological formations directly below the receiver. Seismic migration is an image reconstruction technique which depropagates the recorded signals back to their correct subsurface spatial positions based on wave theory considerations, thus enhancing the lateral resolution. However, a drawback of the conventional migration methods is that the user has no control over the final migration image after specifying the velocity field. To prevent any improper interpretation of seismic data, a reliable velocity analysis algorithm

[1] Institute of Seismology, National Chung Cheng University, Chiayi, Taiwan, R.O.C.

is required. Many velocity analysis algorithms have been published and discussed (Binodi, 1992; Bishop, *et al.*, 1985; Deregowski, 1990; De Vries and Berkhout, 1984; Faye and Jeannot, 1986; Harlan, 1989; Ivansson, 1986; Kim and Gonzalez, 1991; Lafond and Levander, 1993; MacBain, 1989; MacKay and Abma, 1992; Sena and Toksoz, 1993; Stork and Clayton, 1991; Toldi, 1989; Versteeg, 1993; and Yilmaz and Chambers, 1984). Although different algorithms have pointed out their advantages and disadvantages, conventional methods require a prior knowledge of the detailed velocities and shape of the layer boundaries. Unfortunately, as known in the past, such answers are not always possible.

Shih (1990, 1991 and 1992) and Shih and Levander (1994) had successfully developed a layer-stripping reverse-time migration technique, which showed superior imaging capabilities over data with complex structures. Using the layer-stripping migration technique, only an approximate velocity with approximate boundaries is needed. The exact velocities and interfaces between layers are determined during migration. The layer-stripping reverse-time migration algorithm preserves the advantages of the reverse-time method. In addition, this migration algorithm allows for the interpretation of one individual step of migration.

Although the layer-stripping migration technique provides a satisfactory migration image, migration with constant velocities in each layer is roughly equivalent to a brute stack, which results in some choppy features in the migration (Shih, 1990). To further improve the migration image, it is necessary to detail the velocity function. In other words, a better image could be obtained by using a focusing technique which more accurately determines migration velocities.

Determining the migration velocity is a very important step to prevent the improper interpretation of seismic data. Al-Yahya (1989) used post-migration common-depth gather to analyze pre-stack migration velocity, by which he examined the alignment of migrated events on migrated common-reflection point gather. This method shows great forseability in effectively analyzing migration velocity. Incorporating this with the migrated common-reflection point gather, the authors have further expanded the layer-stripping migration scheme become a powerful iterative migration technique with velocity analysis embedded.

In this paper, the idea of the proposed iterative migration algorithm is shown. The procedures of migration and velocity analysis are described. The migrations of synthetic seismic data sets are used to illustrate the capability of the proposed migration algorithm. Additionally, the sensitivity of the error of the initial velocity to the accuracy of migration results are discussed.

2. VELOCITY ANALYSIS AND THE ITERATIVE MIGRATION ALGORITHM

To achieve an accurate migration image, an accurate velocity function is definitely required. In general, stacking velocities, refraction velocities or velocities from nearby wells are used to provide an initial velocity model. The initial velocity model is then modified according to the migration results. Velocity analysis is a quantitative tool for correcting the given initial velocity function.

Al-Yahya published a velocity analysis algorithm (1989) which used migrated seismic data in the so called post-migration common-depth gather to analyze velocity. His method has been found to be an excellent way of judging the accuracy of the velocity function. Figure 1 shows the idea of the post-migration common-depth gather. Figure 1a shows ray paths of reflected waves from different shots. In pre-stack migration, the migration result from each shot forms only a partial image. All of which must be composited to form the final image (Figure 1b). Data compositions are actually the same as stacking migrated signals at the same reflection point from different shots. Seismic signals in a migrated common-depth gather are reflected from the same points at the same depth. If these events are aligned together, this gather is called a migrated common-depth gather. Figures 1c displays common-depth gathers, which are stacked to form the images at positions A in Figure 1a. If the migration velocity was chosen correctly, since the seismic signals were reflected from the same depth, these events should be aligned horizontally.

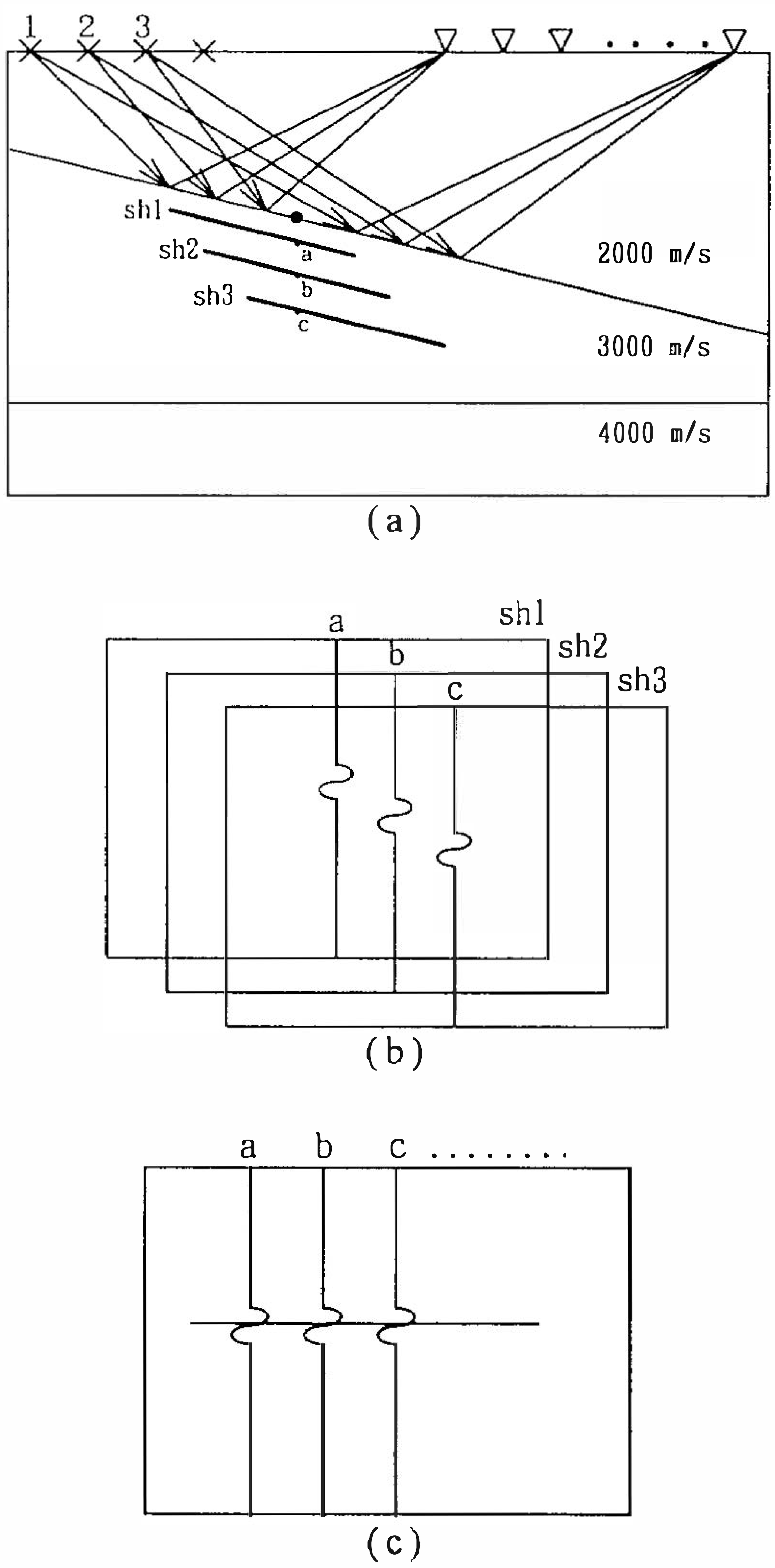

Fig. 1. The idea of the post-migration common-depth gather. (a) shows ray paths of reflected waves from different shots. (b) shows migration results from different shots. These partial images must be composited to form the final image. (c) displays common-depth gathers, in which velocity is chosen correctly. Since the seismic signals were reflected from the same depth, these events must be aligned horizontally.

According to Al-Yahya (1989), the two-way travel time of seismic signals in a migrated common-depth gather can be expressed as:

$$t = 2\sqrt{x^2 + z^2}/\nu, \tag{1}$$

where t is the two-way travel time, x is one half of the horizontal distance between a shot point and a receiver, z is the depth of the reflector and ν is the medium velocity. If migration velocity ν_m is used for migration, the migration depth z_m is obtained, which is different from true depth, unless the correct velocity ν is given. The two-way travel time for migration velocity ν_m is expressed as:

$$t = 2\sqrt{x^2 + z_m^2}/\nu_m. \tag{2}$$

Combining Equations 1 and 2 yields

$$z_m = \sqrt{\gamma^2 z^2 + (\gamma^2 - 1)x^2}, \tag{3}$$

in which

$$\gamma = \nu_m/\nu. \tag{4}$$

As may be seen from Equations 3 and 4, while the migration velocity is equal to the medium velocity, then γ is equal to 1. In this case, the migrated depth is equal to the true depth. If the correct migration velocity is chosen, migrated signals in a common-depth gather should be aligned horizontally. When the chosen migration velocity is too low, then γ is less than 1. In such a case, the migration depth is less than the true depth, and the migrated signals in a common-depth gather curve upward. If γ is greater than 1, i.e. the migration velocity is too high, then the migration depth is greater than true depth, and the migrated signals in a common-depth gather curve downward. These results are structure independent.

The migrated common-depth gather is an appropriate one for analyzing velocity in pre-stack migration. In practical, it is difficult to check if γ was equal to one for all events since migration depth z_m depends on the given migration velocity ν_m. Alternatively, according to Equations 3 and 4, a given γ and depth z may be used to obtain a curve, which gives the migration depth z_m as a function of the surface positions of x.

Summing seismic signals along the above curve, the largest result is then used to determine the value of γ and to correct the initial velocity. The flow charts of the velocity analysis algorithm are displayed in Figure 2. Figure 2a shows the procedures of velocity analysis in the top most layer. According to Equation 4, after the value of γ has been determined, the true velocity ν may be determined. From ν, the depth z of the bottom of the first layer is then computed.

The above analysis allows for the use of one single iteration of migration to determine the media velocity of the first layer. For layers beneath, the determined velocity after one iteration is an average velocity, as worked out from the first layer down to the bottom of the processing layer. Fortunately, the interval velocity can be determined by using the above method after several iterations.

Figure 2b shows the procedures of the velocity analysis of the layers beneath the first layer. From the second layer downward, γ is used as an index to show if migration velocity is too high or too low. The average velocity calculated from the determined γ is used to

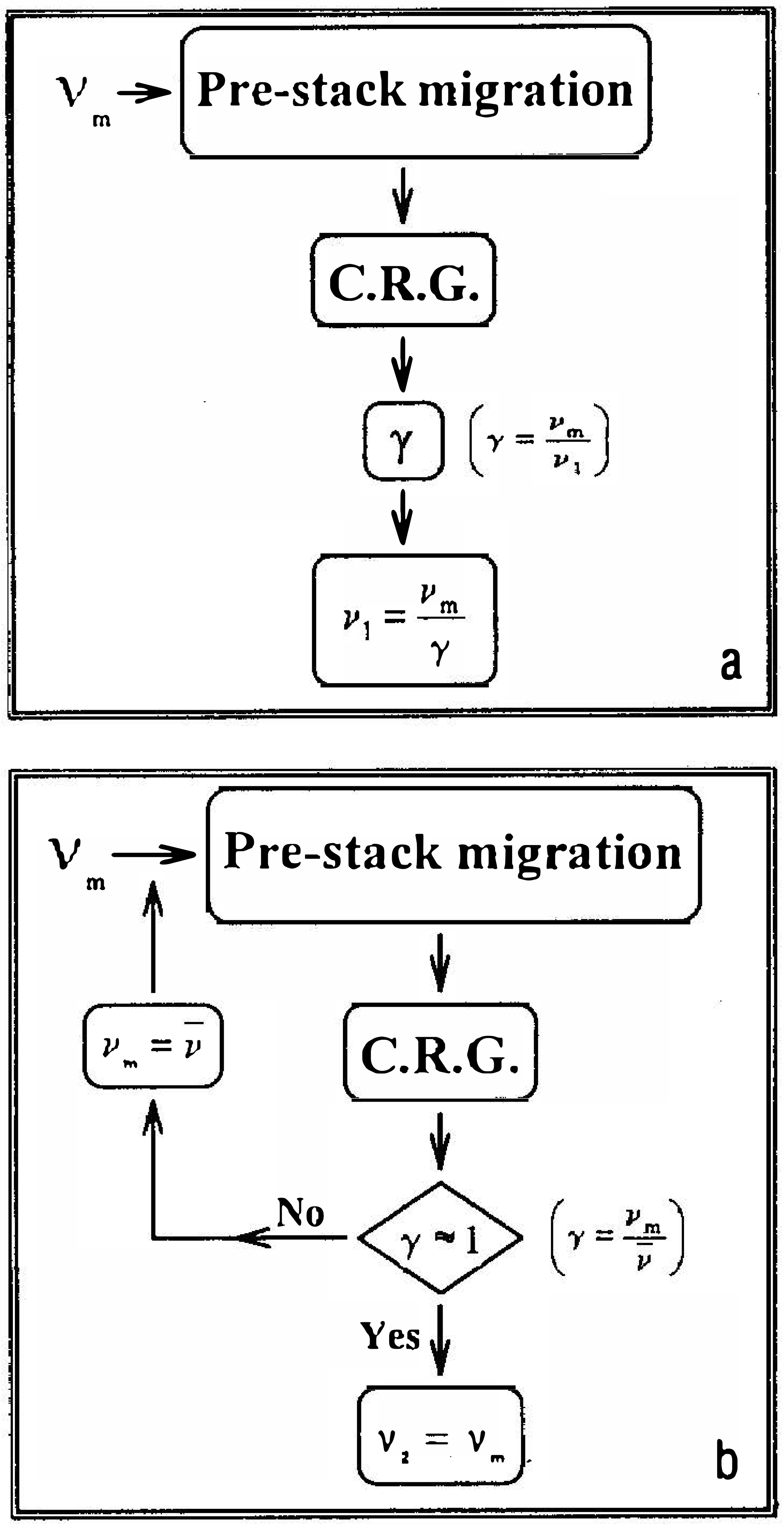

Fig. 2. Flow charts for velocity analysis. (a) shows the procedures for analyzing velocity in the first layer. (b) shows the procedures for the second and the subsequent ones.

migrate the seismic data again until γ approachs 1. In this case, according to Equation 4, the medium velocity of that layer can be determined.

Incorporating conventional migration algorithms and Al-Yahya's (1989) velocity analysis method, it becomes much easier to obtain average velocities, instead of interval velocities. Layer-strpping reverse-time migration migrate one layer at a time, which makes it much easier to obtain interval velocity. Incorporating the migrated common-depth gather, the layer-stripping migration algorithm may be developed to become a popular migration technique. In the proposed algorithm, first an approximate velocity of the first layer is given. Then the migration velocity is corrected from the analyzed γ, and the original shot records are migrated again. The bottom boundary of the first layer is decided after 2 iterations of migration. After that, the wavefield recorded at the surface is downward propagated to the new boundary and used for migration in the following layers. In migrating the following layers, the correct migration image is achieved after a few iterations of migration. The above migration procedures are repeated until the bottom of the velocity model is reached.

An example of migration is shown in the next section. This method may be further developed as an imaging focusing technique and may be adapted to a seismic inversion algorithm.

3. EXAMPLE OF ITERATIVE MIGRATION WITH VELOCITY ANALYSIS

Synthetic seismic data used in this study were generated by using a 4th-order accurate finite-difference forward modeling program (Chen, 1995). The velocity model used in this example is shown in Figure 3, where the model is 3000 m wide and 2000 m in depth. The dominant features of the velocity model are faulted layering sequences, with velocities of 2000, 2500 and 3000 m/sec for each layer, respectively. Forty-six shot records were generated to simulate a 119-channel split-spread shooting geometry, where the shots were positioned at the 60th trace location. A shot interval of 40 m, receiver spacing of 10 m and a maximum offset of 600 m was used in the forward modeling. Two-second seismic data were recorded at a sample rate of 1 ms.

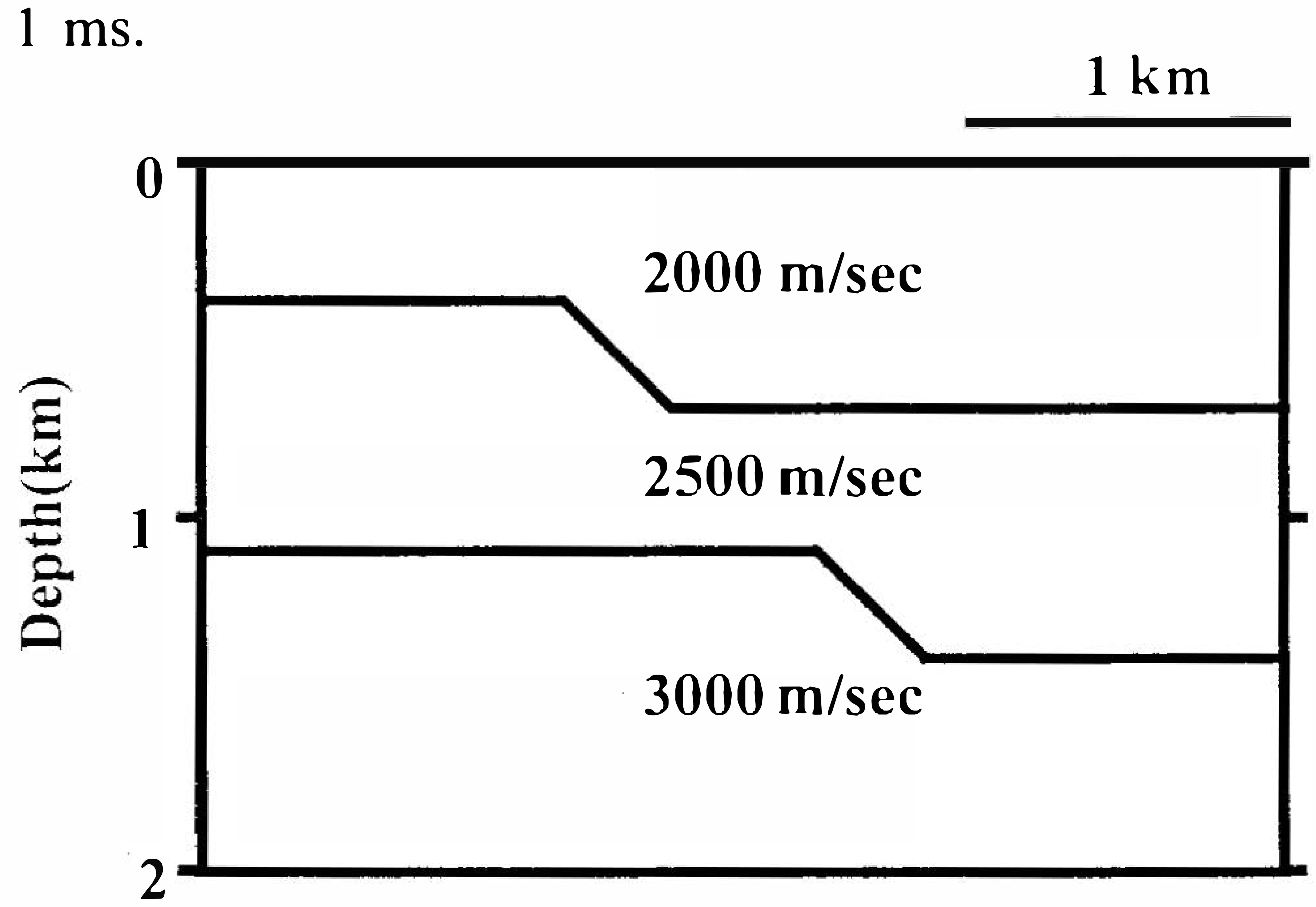

Fig. 3. Velocity model used for migration. The model is 3000 m wide and 2000 m deep. Velocities of 2000, 2500 and 3000 m/sec are assigned to the velocity model, respectively.

Using the layer-stripping scheme, the velocity model was first assigned as one single layer, 3 km wide and 2 km deep. A velocity of 2500 m/sec was used for migrating the first layer. Migration was performed using a rectangular finite-difference grid, in which the horizontal grid size was chosen as 10 m, equal to the receiver interval, while the vertical grid spacing was chosen as 5 m. Pre-migration processing of the shot records included a 30 Hz low-pass filtering to prevent grid dispersion. Direct waves were also muted in the shot records, forty-six of which were migrated. The individual migration images were then composited to form the image of the bottom of the layer. Velocity analysis was done after migration. In this case, γ was made to be equal to 1.24. From Equation 4, the new migration velocity of 2016 m/sec, was close to the true velocity of 2000 m/sec. With the corrected velocity for migration been used, the bottom of the first layer was correctly imaged, not only for the flat layer but also for the dipping faulting surface (see Figure 4).

Then the shot records were propogated to the bottom of the first layer and were used as new boundary conditions for migration to the second layer. In migrating the second layer, the velocity of 3000 m/sec was used, but since this was much higher than the true velocity

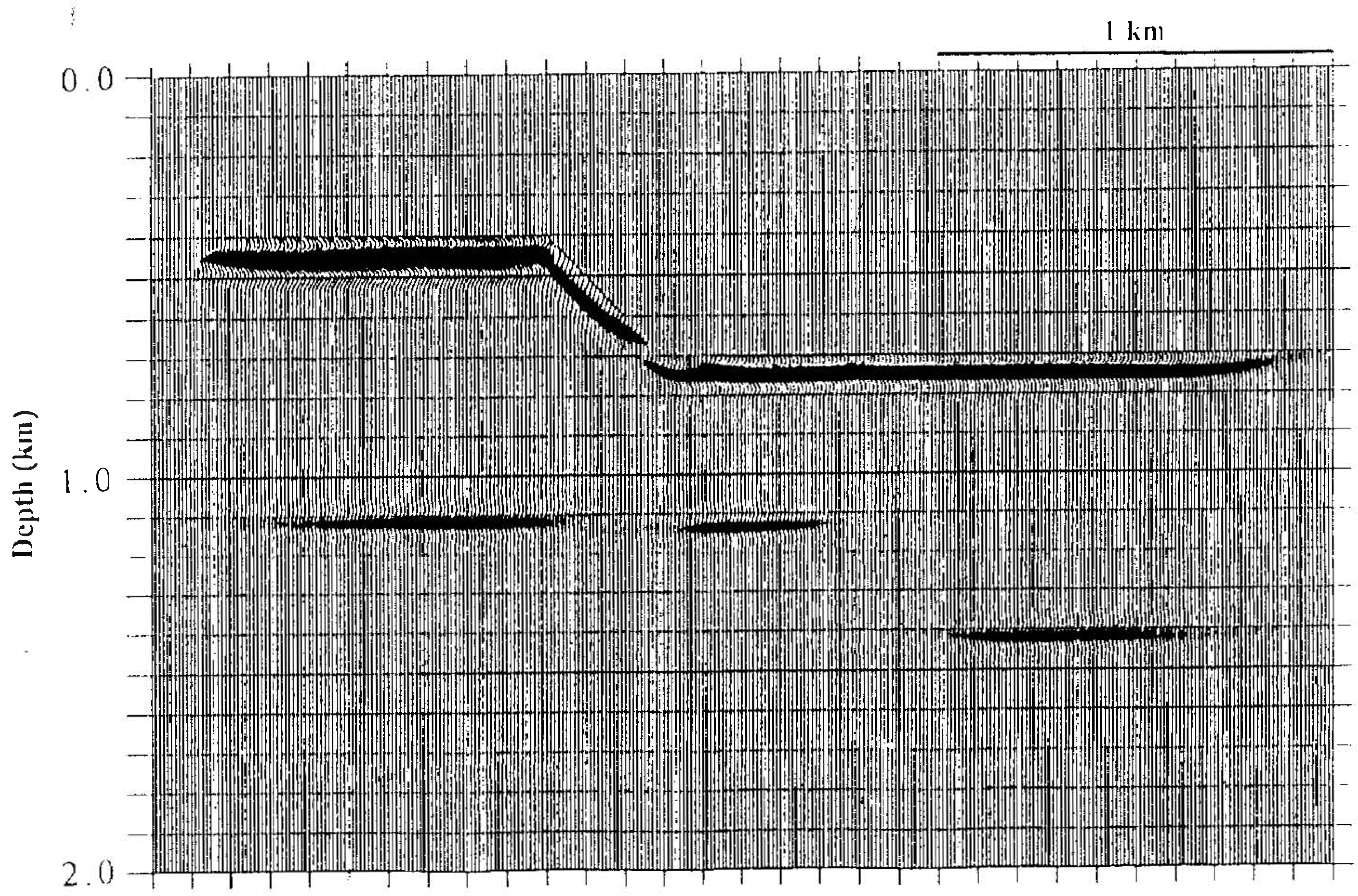

Fig. 4. Migration image of seismic data generated from the velocity model shown in Figure 3.

of 2500 m/sec, the correct migration image was not obtained. After velocity analysis, γ was made equal to 1.092, and the new velocity of 2748 m/sec was obtained. In migrating the first layer, the corrected velocity was very close to the true velocity. Using the proposed migration and velocity analysis algorithms, an accurate migration velocity of the first layer after 1 iteration of migration was obtained. However, 1 iteration of migration was inadequate for analyzing velocity for the second layer and the layers beneath it, as the corrected velocity beneath the first layer was the average from surface down to that layer. The value of γ from velocity analysis is only an index to indicate if the migration velocity was too low or too high. Consequently, 1 iteration of migration doesn't produce a correct migration image.

Fortunately, a correct migration image can be simply obtained after a few iterations of migration. Using the corrected velocity, 2748 m/sec, as a new migration velocity, migration was performed again to get a new value of γ = 1.054, which led to the new migration velocity of 2562 m/sec. This new velocity was then used for migration again, a new γ of 1.022 was found, and a new velocity of 2507 m/sec was given. This velocity was close enough to the true velocity. After another iteration of migration, as expected, the bottom of the second layer was correctly imaged. Figure 4 shows the pre-stack migration results from a 2-layer velocity model. In which the shape and the position of the reflector were correctly imaged and the fault appeared clearly.

4. DISCUSSION AND CONCLUSION

The above example of synthetic data migration has demonstrated the capability of the iterative pre-stack migration of quantitative control over the final migration image. To know the sensitivity of the error of the initial velocity to the migration, the other data set have been migrated. In Figure 5, which shows the velocity model used in the testing, the geometry of

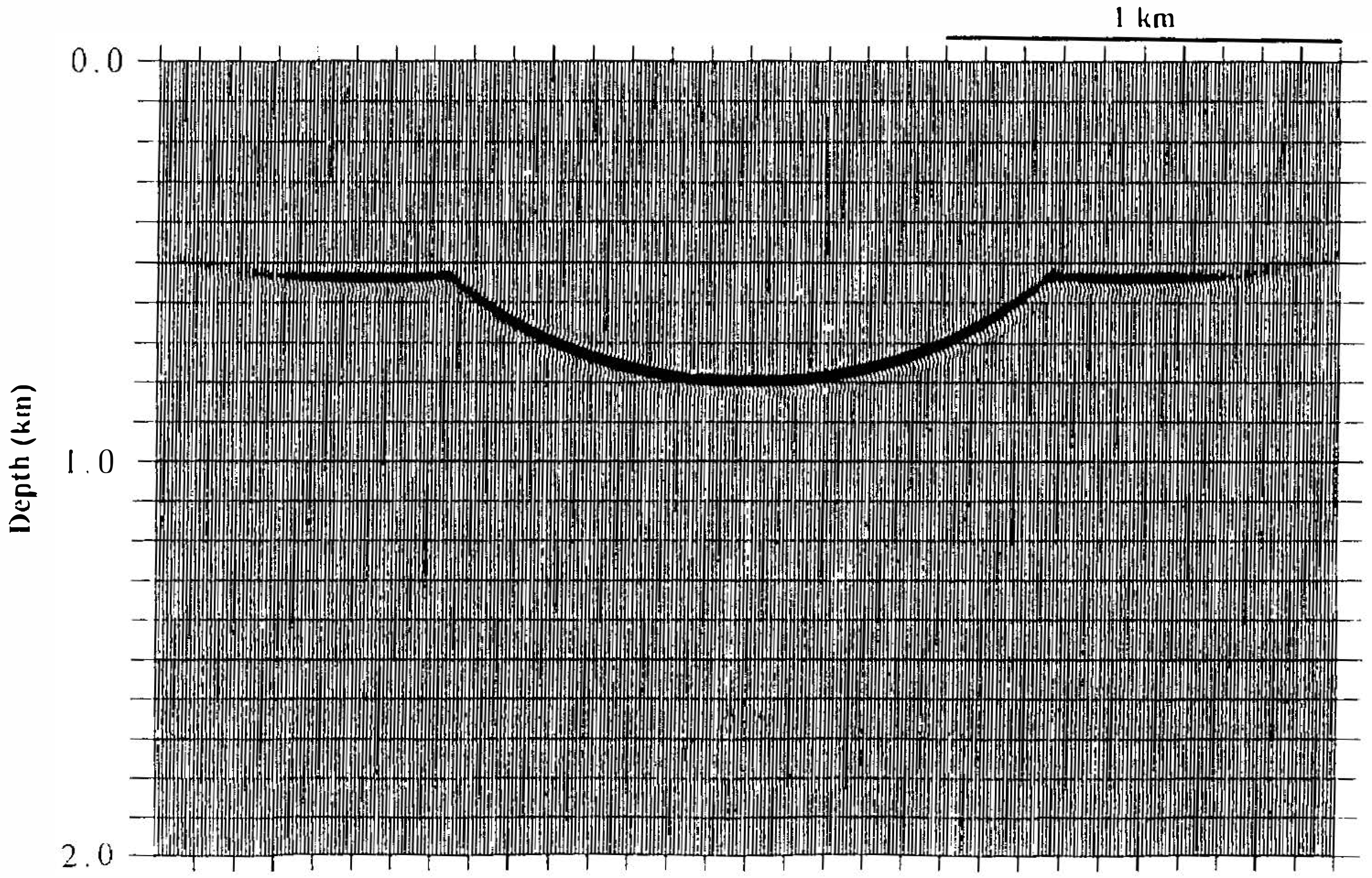

Fig. 5. Migration image of seismic data generated from a model the same as shown in this figure. 500 and 3000 m/sec are assigned of the post-migration common-depth gather. Figure 1a shows ray paths of reflected waves from

the velocity model is similar to that in the previous section, except a more simple structure was used in this instance. To be specific, the 2-layer velocity model was simply divided by a syncline with horizontal interface on both sides with velocity for the first layer at 2000 m/sec and for the second layer at 2500 m/sec.

These initial velocities of 1500, 2000, and 2500 m/sec were used for migrating the first layer. In the first case, with a lower initial velocity of 1500 m/sec being used, the value of γ = 0.772, which led to the corrected velocity of 1957 m/sec. Although this value was not equal to the true velocity of 2000 m/sec, the error was only about 2.15%. In order to attain the correct initial velocity of 2000 m/sec, γ was 0.989, indicating a corrected velocity of 2023 m/sec, and an error of 1.15% from the true velocity. For a higher initial velocity of 2500 m/sec, the value of γ = 1.238. Using this corrected velocity of 2019 m/sec, and an error of about 0.95% was obtained. From these examples, although different velocities were used for migration, all three initial velocities ended up with reasonable results.

Since the wavelet in migration is of concern, even though a correct initial value was given, γ equal to 1 will never be obtained. In other words, the accuracy of the velocity analysis is frequency dependent. Additionally, a 10 Hz low-pass filter was applied to the same data set and migrated it again. After low-pass filtering, in the case of an initial velocity of 1500 m/sec, γ = 0.778 and the corrected velocity was 1946 m/sec. The error of velocity from the true one was about 2.7%, which was higher than the previous example, in which seismic data were filtered with a 30Hz low-pass filter. For the case of initial velocity 2000 m/sec, γ = 0.957, which gave a new velocity of 2090 m/sec, 4.5% away from the true velocity. In the case of an initial velocity of 2500 m/sec, the value of γ was equal to 1.154, the corrected velocity was 2166 m/sec, and the error was 8.3%. All 3 cases clearly illustrated that the lower the frequency of the seismic data, the lower the accuracy of the velocity.

The above synthetic data sets are noise free. Although coherent noises will down grade the quality of the migration image more severely than random noises, in the first stage of the noise added study, the effects of random noises on the proposed migration were tested. With 100% random noises added to the original data set, in the case of an initial velocity of 1500 m/sec, γ = 0.774, the corrected velocity was 1937 m/sec, and the error was 3.15%. In the case of the initial velocity of 2000 m/sec, γ = 1.017, the corrected velocity was 1967 m/sec, and the error was 1.65%. In the case of the initial velocity of 2500 m/sec, γ = 1.257, the corrected velocity was 1988 m/sec, and the error was 0.6%. Obviously, random noises did not severely affect the migration algorithm.

The proposed iterative pre-stack depth migration is a useful migration algorithm, which allows quantitative control over the migration image. The migration scheme is also a powerful iterative velocity analysis tool, eliminating the need to identify events on the shot record in velocity analysis. Although common-depth gather is good at all reflectors position, a low folding number of the data set still down grades the accuracy of the velocity analysis. The proposed iterative migration method can also be used as an image focusing technique, which can be implemented by first varying the velocity field to obtain a roughly horizontally alignment of events on the migrated common-depth gather, and which then can be followed by a fine tuning of the local velocity variations.

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