Optimal aperture width selection and parallel implementation of Kirchhoff migration algorithm

R. RASTOGI and S. PHADKE

Centre for Development of Advanced Computing, Pune University Campus, Pune 411007, India

Summary

This paper describes an approach for selection of aperture width in Kirchhoff time migration and discusses parallel implementation of the algorithm for 2D and 3D data sets. Selection of aperture width in Kirchhoff migration is a crucial factor in obtaining a high-resolution image of the subsurface geological structures. The spatial extent of the diffraction hyperbola used for summation is determined using a combination of the geological complexities and characteristics of the diffraction amplitudes. In this study we propose a new methodology for aperture width selection in Kirchhoff time migration based upon the decay of diffraction amplitude and compare it with two other methods. The parallel algorithms are developed on PARAM10000, a distributed memory parallel computer, using MPI (Message Passing Interface) and MPI I/O parallel programming environment. The effectiveness of this technique is demonstrated by applying it to a data set from SEG/EAGE overthrust model.

Introduction

Seismic migration is an integral part of the data processing sequence that maps the dipping events to their true geological locations and collapses the diffractions at the discontinuities of physical parameters. It is widely used as an indispensable tool for geological interpretation of seismic sections. Kirchhoff migration based upon the diffraction summation approach is one of the most popular techniques in seismic processing industry. In Kirchhoff migration, the amplitudes are summed along the diffraction hyperbola and the result is placed at its apex (Schneider 1976). The aperture width used for the amplitude summation is an important parameter that affects the quality and performance of the Kirchhoff migration.

In this paper we have proposed a new criterion for aperture width selection in Kirchhoff migration. It is compared with two other selection techniques. The first part of the paper discusses different aperture width selection methods. The second part of the paper focuses on the parallel implementation of Kirchhoff time migration algorithm. Highly efficient and scalable algorithm is developed for PARAM 10000 by proper restructuring of the code.

Like other migration techniques, Kirchhoff migration algorithm is also computationally very expensive. To migrate large volumes of 2D and 3D, post-stack or pre-stack data, high performance computers with fast CPUs, large memory, storage and I/O are necessary. Centre for Development of Advanced Computing (C-DAC) located at Pune, developed the OpenFrame architecture for scalable parallel computing applications. Kirchhoff time migration algorithms for both 2D and 3D data volumes are developed and implemented on a 100 GF distributed memory parallel computer, popularly known as PARAM 10000.

Aperture Width Selection in Kirchhoff Migration

In this section of the paper we shall discuss the aperture width selection criterion in Kirchhoff migration. Theoretically the diffraction hyperbolas, along which the amplitude summation is carried out in Kirchhoff migration, extend to infinite time and distance. In practice, we have to deal with truncated hyperbolic summation paths. The spatial extent of the actual summation path, called aperture width, is measured in terms of the number of traces the hyperbolic path spans (Yilmaz, 1987). The curvature of the diffraction hyperbola is governed by the velocity and time. A low velocity hyperbola has narrower aperture when compared to the high velocity hyperbolas. When the medium velocity varies with depth, diffraction hyperbolas have different curvatures at different times. Therefore we need different aperture widths at different times. In the first part of this section, we will discuss the effects of migrating a seismic data set with a constant aperture width method. Then we will look at the migration results with the aperture width based upon the horizontal displacement method. Next we propose a method for calculation of the aperture width based upon the decay of diffraction amplitude. Finally, we compare the proposed method with the other methods and show its effectiveness.

Constant Aperture Width Method

In this technique the aperture width is measured in terms of number of traces, the hyperbolic path spans (Yilmez, 1987). This span remains the same for all time levels. There is no fixed rule for deciding a constant aperture width. Any number of traces can be taken as aperture width or we can decide it according to the maximum horizontal displacement that takes place in migration. A small aperture width causes smearing in the deeper part of the section, which destroys the dipping events and produces spurious horizontally dominant events. A larger aperture width degrades the migration quality in shallower regions. The main reason for this type of behavior of migration with constant aperture with time is that as the time increases the RMS velocity also increases. Therefore, the hyperbolic paths become flattened in time and extended in spatial dimension. The summation using smaller aperture includes only the traces near the apex portion of the diffraction hyperbola, where the dip is nearly flat. Hence, the smaller aperture passes only the flat or nearly flat events and the high velocity dipping events at the later times are destroyed. Large aperture width for shallower events causes summation of amplitudes from the flanks of the hyperbolic paths beyond the recognizable diffraction amplitudes. This degrades the migration quality in the shallower part of the section. The problem is overcome to a great extent by choosing an aperture width as a function of time.

Method Based Upon Horizontal Displacement of Events

Aperture width is closely related to the horizontal displacement that takes place during migration (Yilmez 1987). For any given time the optimal value for the aperture width is defined by twice of the maximum horizontal displacement in migration for the steepest dip of interest in the input section. The half aperture width varying as a function of time is given by

$$N_x(i) = \left(\frac{v_{av}^2(i) \quad t(i) \quad dt/dx}{4} \right) \Big/ \Delta x$$

Where $N_{x,}$ is the half aperture width in terms of number of traces at time sample i, v_{av} is the average velocity, t is the two-way time of the sample, Δt is the sampling interval and Δx is the trace spacing The horizontal displacement is calculated at each time step considering the maximum dip of interest in the input section measured on unmigrated section as dt/dx. This method was applied to a 2D post-stack line of SEG/EAGE overthrust Model (1997). The calculated horizontal displacement near the surface is very small i.e., less then the trace spacing and very large near the basement. In order to make this formula realistic instead of only being theoretical, we defined two parameters lower time cutoff and higher time cutoff. The lower time cutoff is the time near the surface before which, migration required is less. The higher time cutoff is the time level near to the basement after which, not much migration is required. Our aperture width formula is calculated between these two time levels. The graph in figure 1a shows the half aperture-width function as a function of time. The result of 2D post-stack migration using the function of Figure 1a is illustrated in Figure 1b. The noise at the shallower level is reduced and the deeper events have also become clear.

There are some practical problems in this type of approach. If the input section is noisy, then it is difficult to decide about the maximum dip parameter. The lower and upper time cutoffs should also be chosen carefully and are highly subjective.

Method Based Upon the Diffraction Amplitude Cutoff

This approach is based on the basic assumption made in Kirchhoff migration i.e., reflecting interfaces in the subsurface are replaced by points (Schneider, 1976) These points act as Huyguns' secondary sources and produce hyperbolic travel time curves. As these sources get closer to each other, superposition of the hyperbolas produces the response of actual reflecting interfaces. These hyperbolas are equivalent to diffractions seen at a fault boundary on stacked section. These diffractions die down as we move away from the diffracting point (Yilmez, 1987).

Therefore the aperture width in Kirchhoff migration at a particular time level and location in the subsurface, can be determined based upon this criterion. The spatial extent of the hyperbolas for summation can be up to the point where amplitude drops down to a certain percentage of its value at the apex. Berryhill(1997), Trorey (1977) and Phadke (1988) have discussed the diffraction response for a non-zero source and receiver spacing for a diffracting point in a constant velocity medium. For 2D post-stack Kirchhoff migration, we first calculate the diffraction response in the profile direction for coincident source-receiver geometry. For prestack migration the calculations should be done for non-coincident source receiver geometry. The diffraction amplitude is calculated at each CDP location for a fixed diffractor location. The number of traces making up the aperture width is determined at each time sample by the trace location where the amplitude drops to 10 to 50 percent of its valve at the apex. The graph of the decay in diffraction amplitude as a function of distance of the point diffractor from the output location is shown in Figure 2a for various depths of the point diffractor. The amplitude drop for shallow diffractor is more rapid as compared to that of deep diffractor. Therefore the number of traces in the aperture width will increase as the time increases. In this way, we are preserving the trend of hyperbola's shape, which changes with the increase in the velocity and time. For velocity increasing with time, we have a narrow aperture near the surface and wider aperture near basement.

The 2D post-stack time migration results using the proposed aperture-width function are shown in Figure 3. The aperture function may vary with the choice of amplitude percentage cutoff. The graph showing different half aperture-width function is shown in Figure 2b for different diffraction amplitude percentage cutoff. The computation time increases as the amplitude cutoff decreases. We found that for 2D post-stack migration, it is good to use 30 to 10 % diffraction amplitude cutoffs (Figure 3). The deeper events are mapped very sharply in section using 10 percent of amplitude cutoff. However, in the shallower level we see some noise. On the other hand, the migration using 50 % amplitude cutoff shows less noise in the shallower levels but the deeper event are merging with each other and event boundaries are not clearly mapped. For this section, using a 30% diffraction amplitude cutoff, the noise in the shallower region is reduced as well as the deeper events has been mapped clearly.

In case of 3D Kirchhoff migration we use the same method for aperture width selection as in 2D. The only difference is that instead of an amplitude cutoff distance on either side of the migration location, now it is a radius around the migration location. We have a different radius of amplitude cutoff at each time level. This radius varies as a function of average interval velocity of that line at each time level. In the parallel algorithm for 3D Kirchhoff time migration we have used the diffraction amplitude cutoff method for aperture width selection, with a cutoff parameter of 30%. The aperture function is calculated using the average interval velocity of the middle most line. For the sake of uniformity of amplitudes in the migration result, it is recommended to the same aperture function to migrate the whole volume.

Parallel Implementation

The Kirchhoff time migration methods in 2D and 3D are implemented using MPI (Message Passing Interface) and MPI I/O parallel programming environments. The synthetic data set for an overthrust model, provided by SEG/EAGE is used for testing of the codes. The methods were also applied to some real industry data sets.

Recently, cluster of workstations or network of workstations has gained popularity as they provide a very cost-effective parallel-computing environment. PARAM 10000 is a distributed memory parallel computer consisting of 40 nodes. Each node has 4 CPUs and 512 MB of RAM. These nodes are connected by high-speed network (PARAMNet and Ethernet) for communication. Most of the clusters use NFS (Network File System) and MPI (Message Passing Interface) calls to communicate and synchronize between the processors. One limitation of NFS is that the I/O nodes are driven by standard UNIX read and write calls, which are blocking requests. This is not a problem for applications with small volume of I/O, but as the volume increases (as in 3D seismic acquisition), it is necessary to be able to overlap computations with the I/O to maintain efficient operation (Olfield et al., 1998, Poole, 1994). In the present study we have used both MPI and MPI I/O to improve the performance and efficiency of the codes (Bhardwaj et. al. 2000).

Conceptually, MPI consists of distributed support software that executes on participating UNIX / LINUX hosts on a network, allowing them to interconnect and cooperate in a parallel distributed computing environment. MPI offers an inexpensive platform for developing and running application. Heterogeneous machines can be used in a networked environment. The MPI model is a set of message passing routines, which allows data to be exchanged between tasks by sending and receiving messages.

The parallel implementation of the Kirchhoff migration codes, are based upon Master-Worker system. The job of the Master is to provide the required parameters and data to all the workers and distribute workload properly, so that idle time of the workers is minimized. Also at the end Master should collect the finished work from all the workers, compile it and store it in a proper manner. One of the processors acts as Master and the Worker tasks are assigned to different processors. In the Parallel implementation using MPI I/O master does not distributes the data but send only the required parameters to the workers, and identifies the portion of the data to be processed by each worker. Workers read the required input data directly using MPI I/O and process their portion of the data. They also write the migrated results directly on the disk using MPI I/O.

Parallelization of 2D and 3D Kirchhoff migration algorithms is quite straightforward. Figure 4 illustrates the pseudo-code of the parallel algorithm. We use a data parallel approach and parallelize the loop over output location. Master sends the migration locations to each worker along with the corresponding velocity model. Master also calculates the aperture function and sends it to workers. According to the migration locations, master identifies how much input data each worker will require for migrating their portion of locations. In case of 2D migration, the output locations are cdp locations of a line, and in case of 3D, migration output locations are seismic lines. In the parallel implementation without MPI I/O, the master reads and sends the input traces to each worker. Workers then do the phase conversion and migration of their input traces. Finally, they send their respective migrated sections to the master. Master identifies the correct location of the part of the migrated sections it receives and writes it into the output file. In parallel implementation with MPI I/O, master only sends the required parameters for division of migration locations and the velocity model. Workers read their portion of input data directly from the full data volume. They do all the other required calculations and write the migrated output directly to the disk.

We tested the parallel algorithm for 2D and 3D post-stack Kirchhoff time migration by applying it to a data set of SEG/EAGE (1997) Overthrust model and also for some real data sets. The original data of the overthrust model had 101X25 CDP traces with inline spacing of 100m and crossline spacing of 100m. We interpolated this data volume to 401X97 CDP traces to make both inline and crossline spacing 25m for avoiding spatial aliasing. Each cdp trace has 350 time samples with a sampling rate of 8ms. We also prepared the interval and rms velocity models of the same size. Table 1 shows the sizes of the input data and the rms velocity model. The aperture-width is based upon the diffraction amplitude cutoff. A 30 % amplitude cutoff is used for migrating this data set.

Size of input segy seismic data	61MB
Size of rms velocity data	52MB
No. of Worker processors	32
Total execution time with MPI I/O	48 mins

Table 1: Problem size for the 3D data set of Overthrust model and the execution time on 32 processors.

We were trying to study the scalability of the 3D migration algorithm using the SEG/EAGE 3D data set. We found out that it is not possible to run the code on a single CPU machine because of the large memory requirement. We could use a minimum of 8 processors for running this code. Figure 5 shows a bar graph for the execution time as a function of number of processors. From this graph one can observe that the algorithm is scalable. Figure 6 shows the interval velocity model and the migrated data for a part of the 3D volume.

Discussions and Conclusions

In this paper, we have proposed a new method for the selection of aperture width and then described the parallel implementation of Kirchhoff time migration algorithm. The new aperture width selection method is based upon the decay of the diffraction amplitude of a point diffractor. The effectiveness of the proposed method is demonstrated by comparing it with two standard methods. Percentage cutoff is the key parameter in the proposed method and affects the performance of the Kirchhoff migration. The less diffraction amplitude cutoff percentage (30% to 10%) gives good results. In view of the noise in the shallower section and clarity of the events in deeper section, we recommend a 30% diffraction amplitude cutoff. The computation time increases if the percentage cutoff is less. A data parallel approach is used for parallelization of the code. Highly efficient and scalable code is developed for PARAM 10000. Since the parallelization is carried out using standard MPI calls, the code can be easily ported across hardware platforms, which support this message-passing environment.

Acknowledgements

Authors wish to thank Department of Science and Technology, Government of India, for funding this project under DCS program and C-DAC, Pune, for providing computational facility on PARAM 10000 and permission to publish this work.

References

Berryhill, J. R., 1997, Diffraction response for nonzero separation of source and receiver, Geophysics, 42, P. 1158-1176.

Bhardwaj, D., S. Phadke and Sudhakar Yerneni, 2000, On improving performance of migration algorithms using MPI and MPI-IO, Expanded Abstracts, Society of Exploration Geophysicists.

Oldfield, R. A., D. E. Womble and C. C. Ober, Efficient Parallel I/O in Seismic Imaging, The Int. J. of High Performance Computing Applications, Vol. 12, No. 3, Fall 1998, pp 333-344.

Phadke, S., 1988, Imaging crustal diffraction zones and seismic tomography, Ph.D Thesis, Department of physics, University of Alberta, Edmonton, P. 65-71.

Poole, J., Preliminary survey of I/O intensive applications, Technical Report CCSF-38, Scalable I/O initiative, Caltech Concurrent supercomputing facilities, California Institute of Technology, Pasadena, 1995.

Schneider, W., 1976, Integral formulation for migration in two and three dimension, Geophysics, 43, P. 49-76.

SEG/EAGE 3-d modeling series No. 1, 1997, 3-D salt and overthrust models, SEG publications.

Torey, A., W., 1977, Diffractions for arbitrary source-receiver locations, Geophysics, 42, P. 1177-1182.

Yilmez, O., 1987, Seismic data processing, SEG publications.

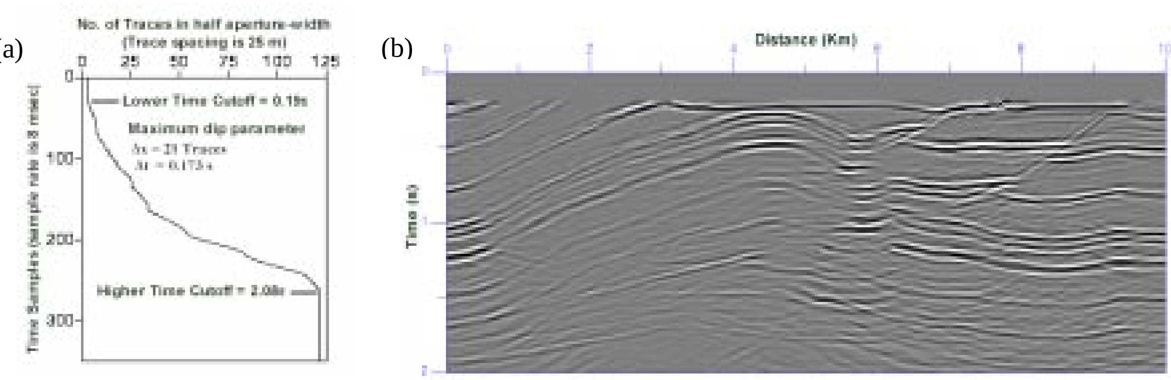


Figure 1: (a) The graph of aperture width function based upon the horizontal displacement. (b) Migrated section of SEG/EAGE overthrust 2D model using the aperture width graph shown in (a).

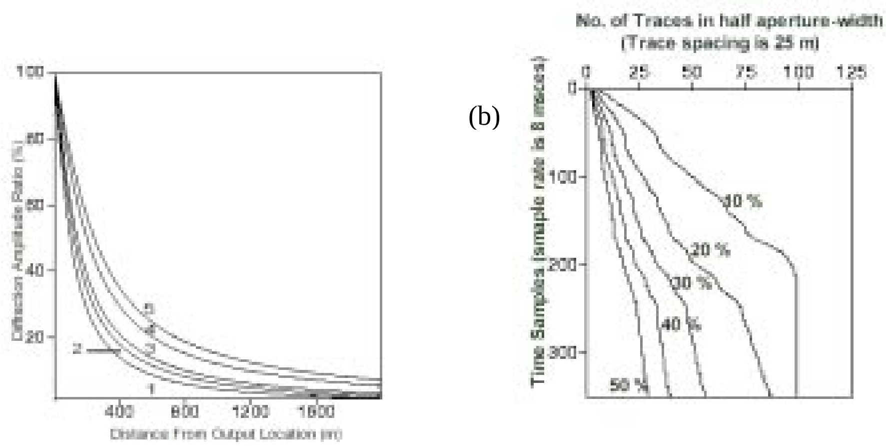
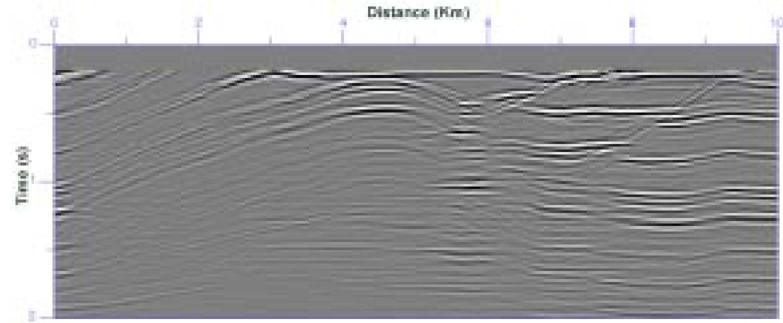
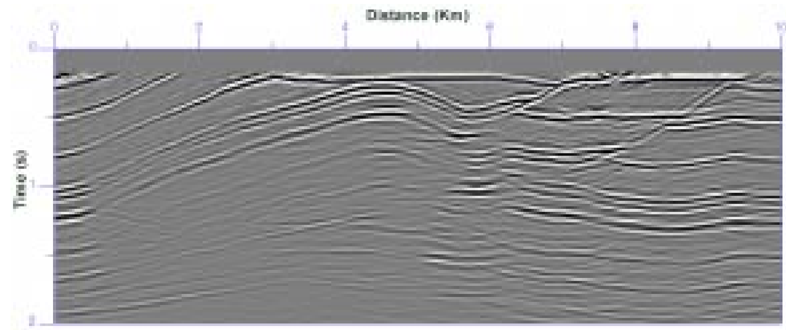


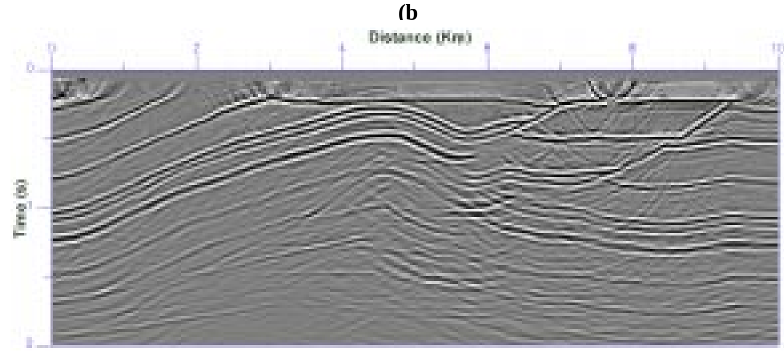
Figure 2: (a) The graph of the diffraction amplitude as a function of the distance from the output location for different depths of the point diffractor. (1. 500m, 2. 750m, 3. 1000m, 4. 2000m, 5. 3000m) (b) The graph of the half aperture width as a function of time samples for different amplitude percentage cutoffs.



(a



(b



(c

Figure 3: Migrated sections of the SEG/EAGE overthrust 2D model with aperture width based upon three different amplitude percentage cutoffs. (a) 50% (b) 30% (c) 10%.

INPUT DATA:

P$_{in}$ (*x, y, t*) → *stacked data in SEGY Format*
V$_{rms}$ (*x, y, t*) → *rms velocity data*

PHASE CONVERSION OF INPUT TRACES

P$_{phase}$ (*x, y, t*) → Apply the 45/90 degree ***phase-shift*** to 2D/3D input traces

Calculate the ***aperture function***

MIGRATION COMPUTATION

For **I** = 1, 2, ….. **No. of seismic lines**. *(for* **3D** *data only)*
For **J** = 1,2, ..., **No. of output locations** *(for* **2D** *and* **3D** *data both)*

```
{
        Calculate the no of cdp required for this migration location
          Using the maximum half-aperture width from the aperture function.
            Get the First and the last input cdp number

        For K = First input cdp, Last input cdp
      {
              1. Calculate the hyperbolic trajectories for each input trace at each
                 time level

              2. Interpolate the input trace and phase-shifted trace using the sinc interpolation

              3. Calculate the obliquity and spherical spreading factors for input
                 trace for each time level

              4. Multiply the interpolated input trace with obliquity factor and multiply
                 the interpolated phase shifted input trace with spherical spreading factor.
                Add both the traces.

              5. Carry out summation of this input trace according to the aperture
                 function of that location for each time level.

      }

        write the migrated traces in the output file according to the output locations.
   }
}
```

OUTPUT

P$_{out}$ (*x, y, t*) → *migrated seismic section*

Figure 4: A Psuedo-code for 2D and 3D Kirchhoff time migration algorithm.

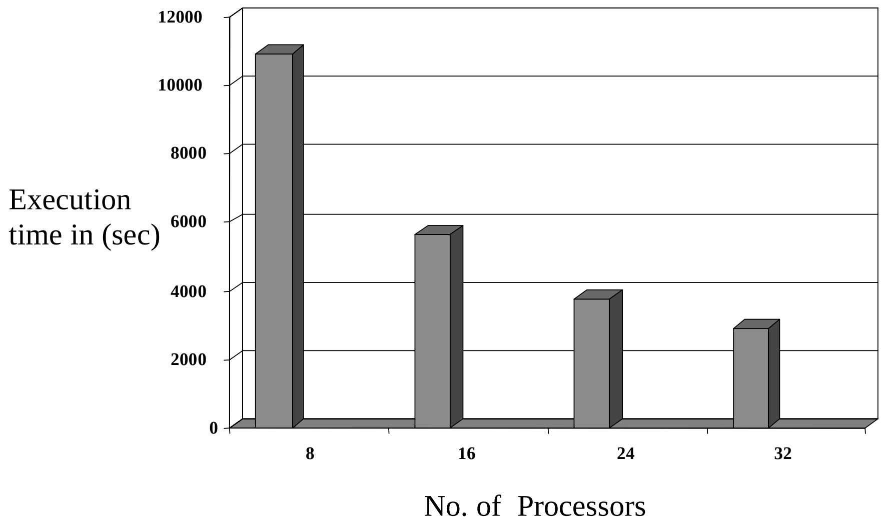


Figure 5: Number of processors versus execution time graph for 3D data set of SEG/EAGE Overthrust model.

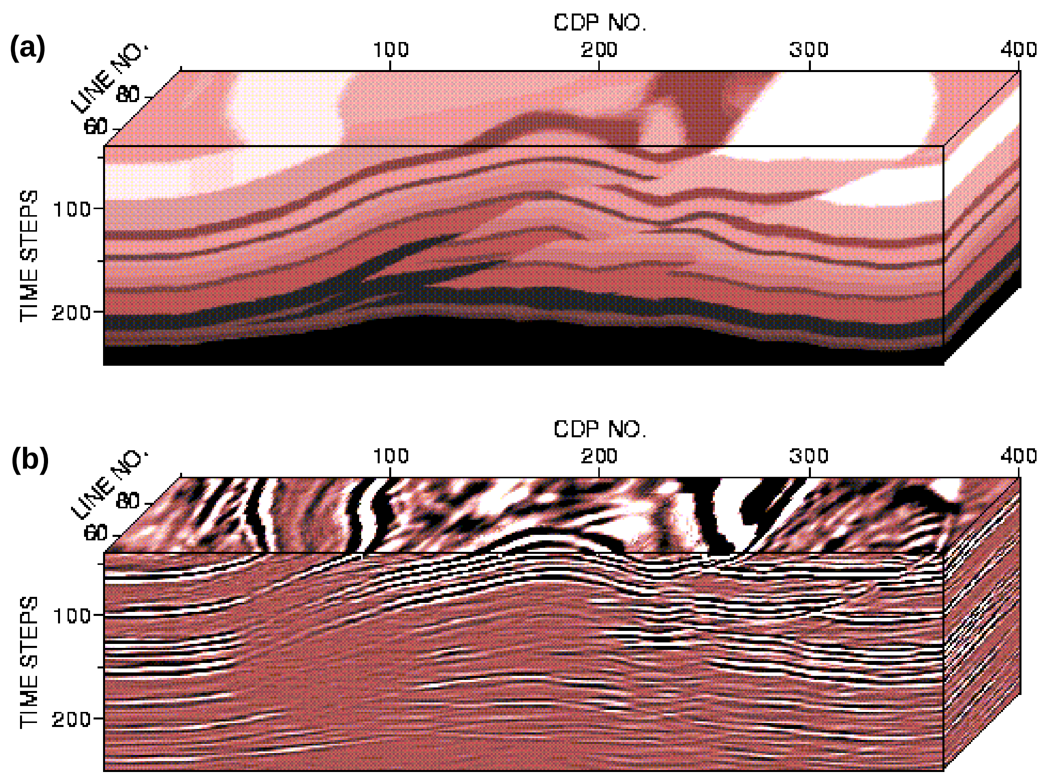


Figure 6: (a) The interval velocity model for a part of the 3D volume of SEG/EAGE overthrust model. (b) The migrated data for the same part of the volume.