Modeling by true-amplitude demigration and its application in time-lapse seismics

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ABSTRACT

Seismic forward modeling is a frequently used technique to produce seismic time sections (seismograms) for inhomogeneous earth models and arbitrary measurement configurations. However, there exist another method to obtain seismograms based on the imaging process "true-amplitude demigration". Starting with a model, an artificial migrated section (AMS) is created and subsequently demigrated to obtain a seismic section which is similar (but not identical) to the forward calculated one. This procedure is called "modeling by demigration" and its application is sometimes advantageous in seismic imaging, e.g., in the simulation of time-lapse seismics (reservoir monitoring). It can be completely integrated in the standard seismic processing chain and, thus, existing (de)migration programs can be readily modified to perform modeling by demigration. The method is able to generate kinematically and dynamically correct seismic sections by using already existing Green's function tables.

INTRODUCTION

True-amplitude (sometimes also called "amplitude-preserving") depth migration is a widely investigated and frequently used process in the world of seismic exploration. However, transforming data from time to depth is only one direction, and one might think about the inverse process, i.e., a concept which transforms data from the depth domain back to the time domain. Many people think that seismic (forward) modeling is such a process, but as Santos et al. (2000a) pointed out this is strictly speaking not correct. Whereas modeling is the inverse operation to migration/inversion, demigration is the real asymptotic inverse operation to true-amplitude migration and aims at reconstructing a seismic time section (primary reflection events) from a depth migrated image. Both processes were intensively studied by Hubral et al. (1996) and Tygel et al. (1996) who established an integral pair to perform the above mentioned transformations from the time to the depth domain and vice versa. This integral pair forms the fundamental key of what they called the *Unified Approach Theory*. The correct treatment of geometrical spreading effects is taken into account by weight functions which are applied during the Kirchhoff-type stacking operations. That means, reflection coefficients are preserved in the processes while ray theoretical geometrical spreading effects of a reflector and the reflector overburden are transformed from those in the input domain to those in the output domain. As a consequence, images contain quantitative information about physical properties of the subsurface. On the one hand, these quantities are useful for reservoir characterization by means of amplitude-versus-offset (AVO) or amplitude-versus-angle (AVA) analyzes in depth migrated sections. On the other hand, they permit to use true-amplitude demigration for modeling purposes. The latter concept is called “modeling by demigration” and was firstly presented by Santos et al. (2000b). This application indicates once again that by means of the *Unified Approach Theory* a fundamental tool is established to perform arbitrary target-oriented seismic transformations and, thus, allows to address a multitude of imaging problems. We will here focus on the principle of “modeling by demigration” and an application in time-lapse seismics. Although the examples presented in this paper are quite simple, they show that the fundamental concept works.

MODELING VERSUS DEMIGRATION

The fact that forward modeling and demigration produce similar time sections leads directly to the question whether both processes are equivalent. As already mentioned, this is not the case. Even though they are closely related, they are in fact two different processes. In general, the term “modeling” means the simulation of a physical process (namely, the wave propagation) given all equations (the elastic or acoustic wave equation) and parameters, e. g., the velocity and density distributions of the underlying earth model and proper initial and boundary conditions, for its complete description. The resulting modeled seismograms should be equivalent (at least in parts) to the recorded data if the same experiment had actually been carried out in the field. Demigration aims at reconstructing a seismic time section from a corresponding depth migrated section, i.e., it inverts the process of migration. As opposed to direct forward modeling, we do not have to know all the true model parameters precisely to actually perform the demigration process. Neither the true velocity distribution in the earth, nor the source wavelet, nor the position of reflecting interfaces have to be known in order to apply a demigration. All that is required, apart from the input depth migrated section, is the macro-velocity model that has been used for the migration process. Even if this velocity model was very poor and, thus, the depth migrated images were not correct, a subsequent demigration would correctly reconstruct the original time sections.

Comparing the modeling integral (see, e.g., Frazer and Sen, 1985) and the demigration integral (see, e.g., Tygel et al., 1996) shows the similarities between both processes. But besides the different stacking surfaces two conceptual differences can be observed: Firstly, there exist a difference between the weight functions. This difference, however, is not a fundamental one as both factors are identical at the specular reflection point. The reason is that the factor in modeling is calculated with respect to the reflector normal whereas the one of the Kirchhoff demigration integral is calculated with respect to the isochron normal. Secondly, there exist a more basic difference between both processes: Kirchhoff demigration needs a stretch factor which appears in the input (migrated image) of the process. Kirchhoff forward modeling does not need to incorporate a stretch factor because it is not an inverse operation to migration but an independent solution of the wave equation.

To illustrate the above statement, let us look at the processes in the context of inverse operations. If Kirchhoff modeling is applied to a certain model containing a target reflector, and then a subsequent Kirchhoff migration is applied to the resulting synthetic reflection data using the same velocity model for both operations, then the migration result will approximate the reflector. Kirchhoff migration only reconstructs the source wavelet along the reflector position. The peak amplitude of the migrated pulse, which is stretched by a certain factor, represents the reflection coefficient (of course, only if the process has been carried out as true-amplitude and the source strength is known). In this sense, migration does not reconstruct the original model. Even though Kirchhoff migration is often understood as the inverse to Kirchhoff modeling, we need to add another process to rebuild the initial model, namely seismic inversion. This additional step is necessary to extract the model parameters and the reflector locations from the migrated image. In other words, only migration with a subsequent inversion is a complete inverse process to modeling. Now, let us apply Kirchhoff true-amplitude migration to some field data and afterwards a demigration to the resulting migrated image. If the same macro-velocity model is used for both operations, then the demigration result can be expected to closely reconstruct the original field data. Thus, Kirchhoff demigration can be understood as the true (asymptotic) inverse operation to Kirchhoff migration.

Hence, we can recapitulate that Kirchhoff modeling and demigration are two processes that are strongly related but not identical. Whereas demigration is the inverse process to migration, modeling is the inverse operation to migration/inversion.

THE CONCEPT OF MODELING BY DEMIGRATION

The above mentioned relationship between Kirchhoff migration, demigration, and modeling makes it obvious how to use true-amplitude demigration for modeling purposes: we have to add another process which has to be an inverse operation to the approach of seismic inversion. That means nothing else than the simulation of a corresponding depth migrated section for a given subsurface model. The section should be equivalent to the one obtained from a previously applied migration. The time section obtained by demigration of this artifical migrated section (AMS) will then be a counterpart of the seismic time section calculated by direct forward modeling in the original subsurface model.

To simulate a true-amplitude depth migrated reflector image, we have to correctly scale and stretch the source wavelet and place it along the reflector in the subsurface model. Mathematically, we can write

$$AMS(x, y, z) = R_c \cdot F\left[m_D(z - \Sigma_R)\right] \ , \tag{1}$$

where R_c is the (plane-wave) reflection coefficient, m_D is the stretch factor, Σ_R the representation of the reflector under consideration, and F is the source wavelet. Figure 1 shows graphically the way from the initial model to the final seismograms using modeling by demigration.

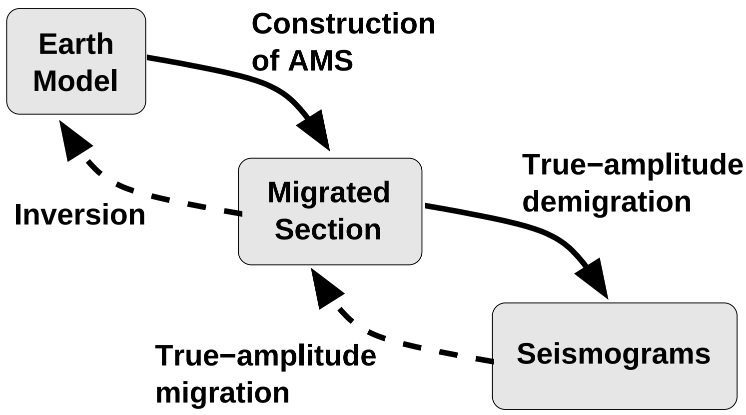


Figure 1: The working scheme of modeling by demigration (solid arrows) and the inverse operations (dashed arrows).

A question which is still unanswered is: Why should we use Kirchhoff demigration for modeling purposes instead of the conventional Kirchhoff modeling integral or other seismic modeling schemes? There exist indeed several reasons why modeling by demigration represents a profitable alternative to generate synthetic seismograms. Due to the similarity between Kirchhoff migration and demigration, highly developed and very efficient, already existing migration programs can be readily modified to include the demigration as well as the modeling part. Therefore, seismic modeling can be performed with a software that is also useful for reflection-imaging purposes. Moreover, the Green's functions needed for migration and demigration are identical. Thus, when applying demigration (either for modeling or imaging purposes) using a velocity model for which some time-domain data have been previously migrated, the Green's functions are already available. A circumstance which is important with regard to the costs of this processing step. Modeling by demigration turns out to be a particularly advantageous process when effects of reservoir changes have to be investigated as is the case for time-lapse imaging. As only the reflector properties change but not the overburden with its propagation effects, the same Green's functions can be used several times for subsequent modeling. In this context, modeling by demigration is superior compared to other schemes that have to start all over again. However, Kirchhoff demigration keeps to be a process as expensive as migration—a disadvantage especially when considering an isolated demigration process or a model with only a few reflectors. In such cases, forward modeling might be preferable.

In the case of using modeling by demigration for the simulation of a seismic zero offset (ZO) section, the idea of constructing an AMS can be directly applied. All necessary quantities (i.e., the stretch factor and the reflection coefficient) are physical parameters directly available from the a-priori specified earth model. For a ZO measurement configuration, the stretch factor is given by $m_D = 2\cos\beta/v$ and the reflection coefficient by $R_c = (\rho_2 v_2 - \rho_1 v_1)/(\rho_2 v_2 + \rho_1 v_1)$, where β is the local dip of the reflector under consideration, and $\rho_{1,2}$ and $v_{1,2}$ are the densities and velocities above and below the interface at the reflection point.

In the case of finite offset configurations, however, the stretch factor as well as the reflection coefficient depend on the reflection angle of the specular reflected ray between the source and the receiver. That means, for each different source-receiver pair a differently scaled and stretched wavelet has to be used because the reflection angle varies. As this angle is not available before doing the actual modeling step, it seems that the strategy of modeling by demigration fails for finite offsets. The problems, however, can be circumvented by constructing the AMS not explicitly but implicitly *during* the demigration procedure using information of the reflector location and curvature. This strategy can, of course, not be followed for a true demigration but is a reasonable procedure for modeling by demigration. The specular reflection angle is estimated at each summation step from the Green's function to determine the isochron stacking surfaces and weight functions. Then, the stretch factor m_D and the reflection coefficient are computed during the demigration process. In this way, the AMS is implicitly simulated during the stack at each point of the isochrone. For further details, the reader is referred to Santos et al. (2000b).

NUMERICAL EXPERIMENT

To illustrate the method, we consider a simple model. It consists of one reflector which separates two homogeneous half spaces. The velocities are given by $v_1 = 2.0$ km/s and $v_2 = 2.4$ km/s, respectively. The density was chosen to be constant and equal to unity. Figure 2 shows the model and the ZO ray family used in this experiment.

As mentioned in the sections above, the modeling process using demigration consists of (1) transforming the given subsurface model into a fictitious, true-amplitude migrated image (AMS), and (2) applying a demigration to this AMS. Figure 3 shows the artificially constructed migrated reflector image obtained from the model parameters according to equation (1).

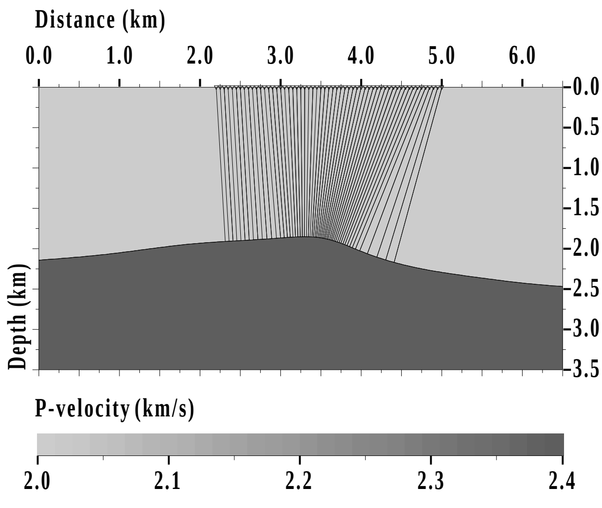


Figure 2: Simple model used for a numerical experiment. The shadings denote the P-wave velocities. For simplicity, the density is constant in the whole model. The lines denote the ZO ray family.

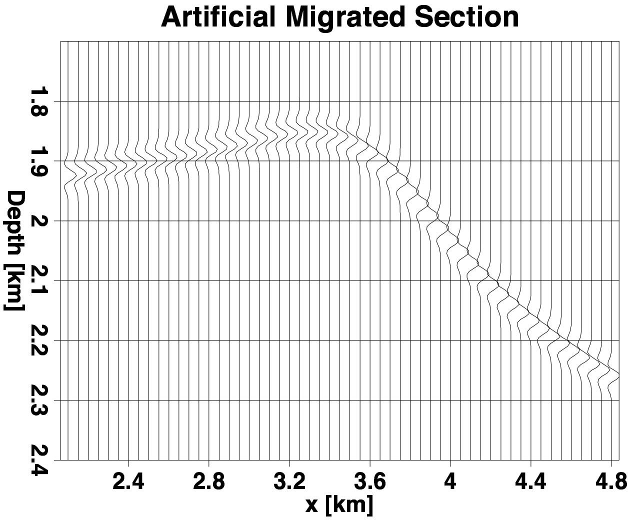
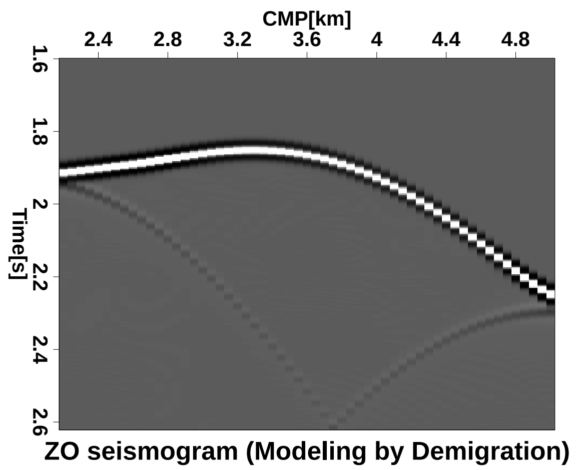


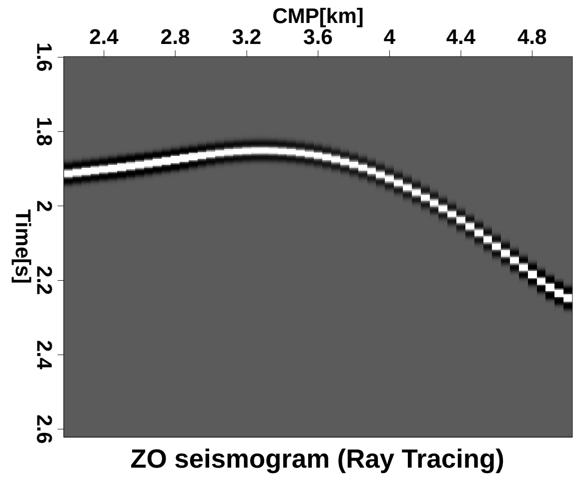
Figure 3: The artificial migrated section valid for ZO modeling, constructed from the model shown in the Figure 2. This section was built according to equation (1) with $v_1 = 2.0$ km/s, $v_1 = 2.4$ km/s, and $\rho = 1$ g/cm^3.

Using the AMS, Figure 3, as input for the demigration process yields the zero offset seismograms shown in Figure 4(a). This seismic section has 57 shots/receivers (CMP locations) with an aperture of 2.85 km from 2.15 km up to 5 km and a trace distance of 50 m. Remember, because demigration is the (asymptotic) inverse process to migration, the wavelet stretch is removed, i.e., the resulting seismograms contain the unstretched zero-phase Ricker wavelet. For reasons of comparison, the same experiment has been simulated using a conventional seismic forward modeling scheme (based on ray theory). Figure 4(b) shows the corresponding seismic section. It is hard to recognize any difference between both seismograms, besides the boundary effects which occur using modeling by Kirchhoff demigration. These effects can be easily suppressed by taper functions applied during the stacking operation. However, we made no special disposition to avoid the effects to emphasize that modeling by demigration uses a conceptually different approach than conventional modeling by ray tracing.

A closer inspection of the results is provided in Figures 5(a) and 5(b). The comparison of the traveltimes clearly shows that there is no difference concerning kinematic aspects of the demigrated and modeled seismograms. The traveltimes picked at the peak amplitudes coincide in every trace. The comparison of the amplitudes shows some discrepancy, especially in regions where the amplitude changes quickly. Modeling by demigration smooths the amplitude behavior which is due to the fact that—as opposed to ray tracing—modeling by demigration is based on a stacking process which always entails smoothing of the data. However, this smoothing effect might also be desired because it provides a more “natural” behavior of the amplitude compared to ray tracing. This aspect needs further investigations.

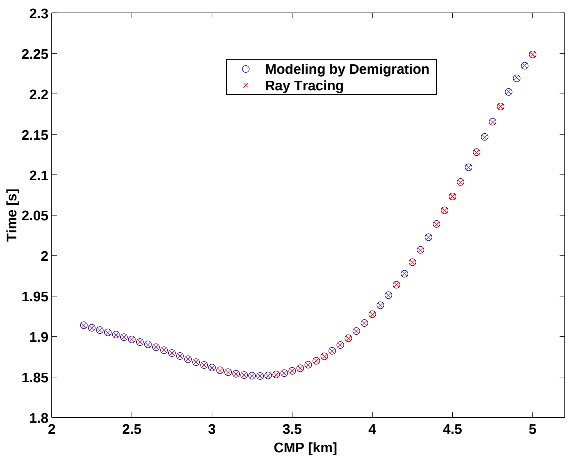


(a) Demigrated seismogram

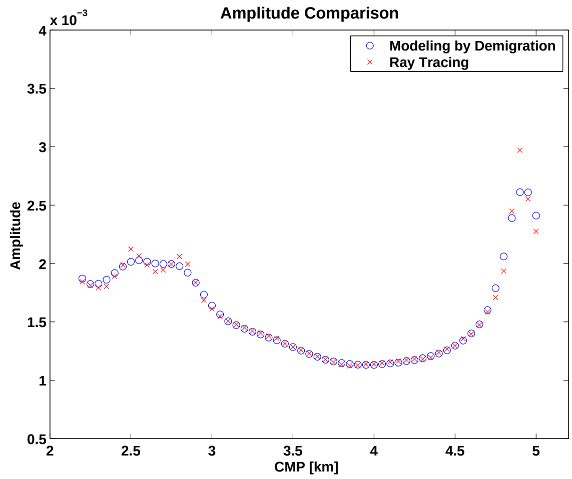


(b) Modeled seismogram

Figure 4: Comparison of seismograms resulting from (a) modeling by true-amplitude Kirchhoff demigration and (b) conventional seismic (forward) modeling (based on ray tracing). The seismic sections consist of 57 CMP locations within an aperture of 2.85 km, resulting in a trace distance of 50 m. Please note that no taper function was used in the demigration process to point out the different approaches.



(a) Time comparison



(b) Amplitude comparison

Figure 5: Comparison of the (a) traveltimes and (b) amplitudes using modeling by demigration and forward modeling. Both pictures show that kinematic as well as dynamic quantities are (nearly) identical. Modeling by demigration, however, smooths the amplitude behavior.

THE PRINCIPLE OF TIME-LAPSE SEISMICS

A seismic survey over a hydrocarbon reservoir is repeated at different stages of the production process. Production-induced changes of the reservoir properties modify the seismic response. Information about the progress of the production program can be extracted from these data sets by means of suitable processing. So-called difference seismograms can be created by subtracting the seismic data from two subsequent seismic surveys. Difference seismograms are very useful for interpretation because production effects should be associated with amplitude changes in the difference sections. The repeatability of seismic surveys is a critical issue for time-lapse experiments because random variations of the source signal, recording geometry, weather conditions, etc., tend to obscure the desired effects. The availability of special adaptive time-lapse processing techniques like cross-equalization was a prerequisite for the feasibility of seismic reservoir monitoring. Actual time-lapse seismics suffers from a lot of problems and is a real challenge for geophysicists. Entering into this business goes beyond the scope of this paper. Of course, repeatability is not a problem for seismic modeling. Apart from their computational costs, the generation of synthetic difference seismograms is straightforward.

For a hydrocarbon reservoir under development, a detailed geological reservoir model is built. It integrates all available information, including seismic data, well logs, and the production history, to name a few. By accumulating data over time, the reservoir description is continually updated and refined. The main purpose of such a reservoir model is to support development decisions, e.g., concerning the location of new wells. For this task, fluid transport is simulated in the reservoir model for possible production scenarios. By means of relations from rock physics, the results of fluid flow simulations are converted into elastic moduli or seismic velocities. Thus, a set of earth models is generated. The challenge is now the fast generation of synthetic seismograms for all of these models. The most obvious solution would be to choose one of the standard modeling techniques and to do full simulations of seismic wave propagation for all configurations of interest. Generally, both the reservoir and the overburden may have a fine and complex geological structure. Hence, accurate modeling of the complete wave field is required and typically, finite-difference (FD) modeling is the method of choice. Unfortunately, detailed FD calculations consume large amounts of computational resources. Consequently, the more scenarios to be modeled the more expensive and difficult becomes time-lapse modeling. A possible remedy is the usage of modeling by demigration—it represents the link between seismic (forward) modeling and seismic reflection imaging and, therefore, it can use information already available from a previously carried out reflection imaging process.

In order to demonstrate how modeling by demigration can be used to simulate time-lapse experiments, we have applied the technique to the model depicted in Figure 6. It is built up by homogeneous layers whose P-wave velocities are also shown in the picture. Although quite simple compared to actual reservoir scenarios, the 2.5D model suits the requirements to test the applicability of the method presented in this paper. As migration and demigration are target-oriented processes, we have to define a target zone. This target zone includes the "reservoir", i.e., the region of interest with the reference and target reflectors, see Figures 6 and 7(a). In order to simulate a reservoir change, the velocity in the dark gray region (Figure 7(a)) has been changed. As a consequence, the reflectivity at the borders of the "reservoir" changes. Ten different stages of production were simulated by successively changing the velocity below the target reflector; all other velocities were kept constant. The resulting reflection coefficient of the target reflector is depicted in Figure 7(b).

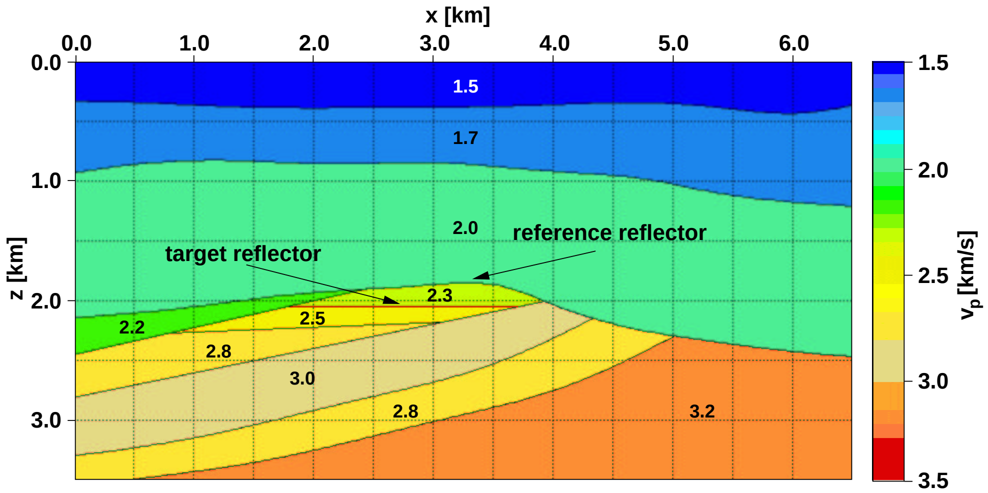
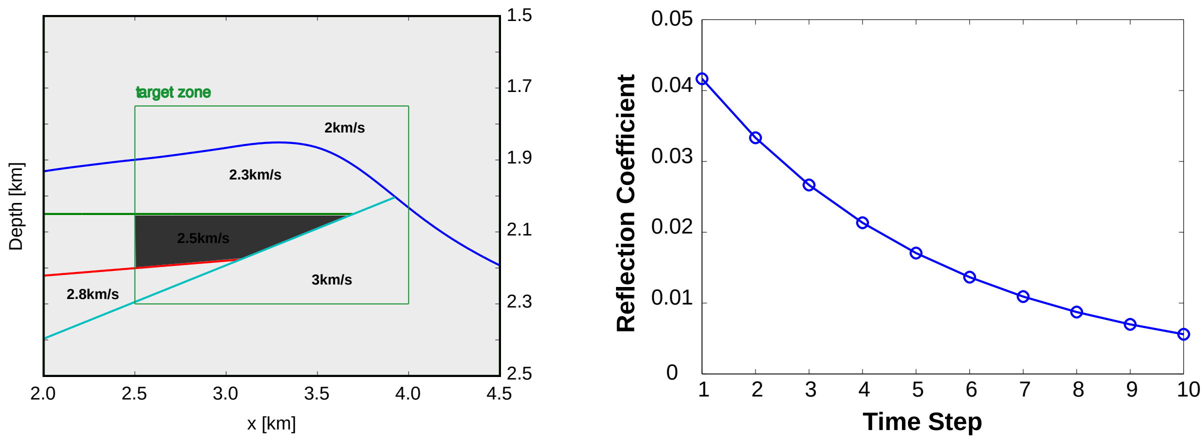


Figure 6: Earth model used to test the process of modeling by demigration for time-lapse seismics. The shadings denote P-wave velocities.



(a) Target zone

(b) Change of reflectivity

Figure 7: The target zone of the model is shown in (a). The reservoir with changing parameters is depicted in dark gray (within the target zone). The upper reflector of the reservoir is denoted the "target reflector". The change in reflectivity of the target reflector due to velocity changes in the reservoir is shown in (b).

Figure 8 shows the artificial migrated sections for the different simulated stages of production. All AMS are displayed in parallel planes to the front face of the data cube. The front face itself shows the AMS that corresponds to the initial velocity model shown in Figure 6. The line at $x = 3.14$ km denotes the location of the panel which is shown at the right side of the cube. One can clearly observe that the reflectivity of the target reflector is decreasing.

In order to demonstrate that the proposed method is able to correctly recover the reflectivity change of the target reflector, ten different seismograms (corresponding to the ten different AMS simulating different production stages) were "modeled by demigration". Figure 9 shows one of the demigrated seismic sections. Diffraction events are automatically produced when using modeling by demigration as opposed to standard ray tracing. Furthermore, Figure 9 illustrates the subsequent processing. Difference seismograms were created in the following way: seismic section no. 1 (obtained with the initial velocity distribution) minus seismic section no. 2 (obtained with a reservoir velocity slightly below the original one); seismic section no. 1 minus seismic section no. 3 (obtained with a reservoir velocity slightly below that of model no. 2), and so on. In the next step, these difference seismograms were transformed to depth by means of a Kirchhoff true-amplitude migration scheme using the same macro-velocity model as for the modeling by demigration step. The result is presented in Figure 10. The data cube contains the nine migrated difference sections which are displayed in parallel planes to the front face of the cube. The line at $x = 2.7$ km denotes the location of the panel shown on the right side of the cube. The front face shows the first migrated difference section. As expected, all reflectors not altered in the AMS disappeared because their reflection response was identical in all seismograms. The amplitude of remaining "reflectors" are directly related to the changes in the reservoir. Note that the different sign of the events at the top and the bottom of the reservoir is due to the fact that the reflectivity contrast for the top reflector decreases in the same way as it is increasing at the bottom of the reservoir.

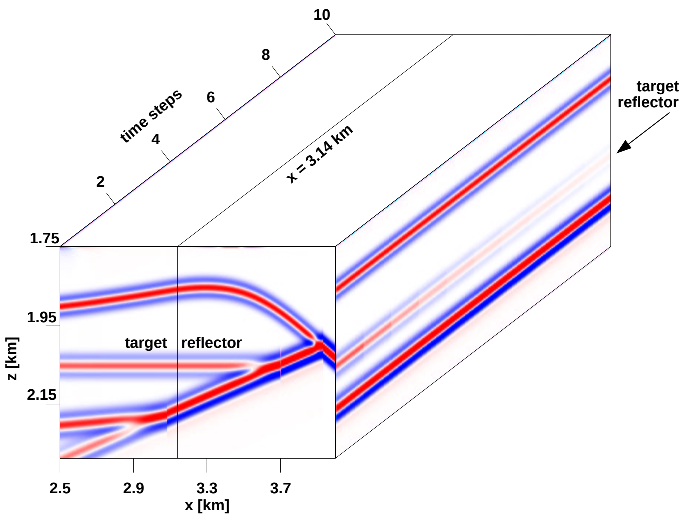


Figure 8: Artificially constructed migrated sections for the target zone shown in Figure 7(a). The right side of the cube shows a panel at $x = 3.14$ km. One can clearly observe the change in reflectivity of the target reflector.

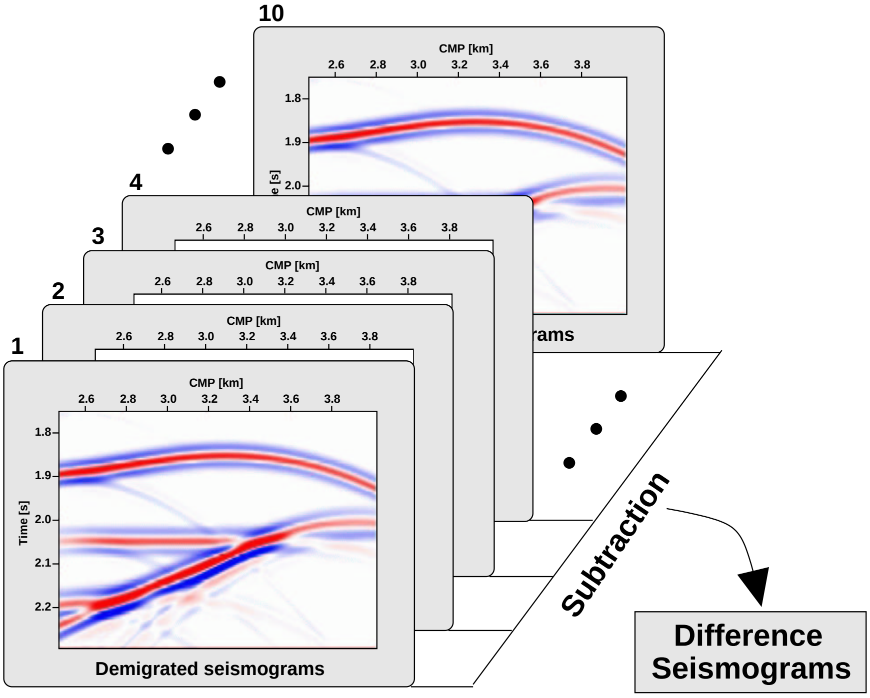


Figure 9: Ten different seismic sections (according to ten different AMS) were "modeled by demigration". They were subtracted to generate difference seismograms. Finally, these different seismograms were migrated.

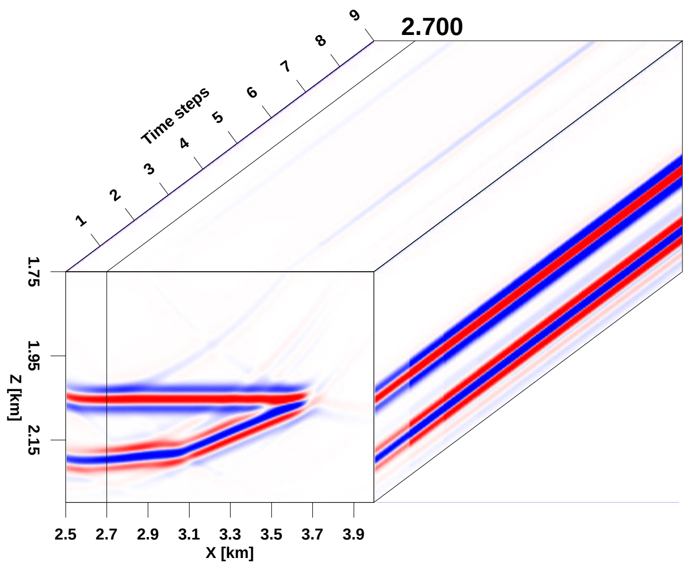


Figure 10: Depth-migrated difference seismograms for every stage of the time-lapse scenario. As only actual changes in reflectivity remain in the difference seismograms, the migrated images show only reflectors around the region where changes occurred. The amplitudes are directly related to the changes in the reservoir.

A quantitative analysis of the migrated difference sections is presented in Figure 11. It shows the picked peak amplitude of the target reflector for every stage of the time-lapse scenario at $x = 2.7$ km (crosses). For comparison, theoretical values that were analytically calculated are plotted as circles. The x-axis denotes the different stages of production. Please note that stage no. 1 in this picture corresponds to the experiment that no changes in the reservoir took place. Therefore, the resulting amplitudes in the migrated difference section are zero. The comparison reveals the accuracy of the method, i.e., changes in the reservoir could be recovered.

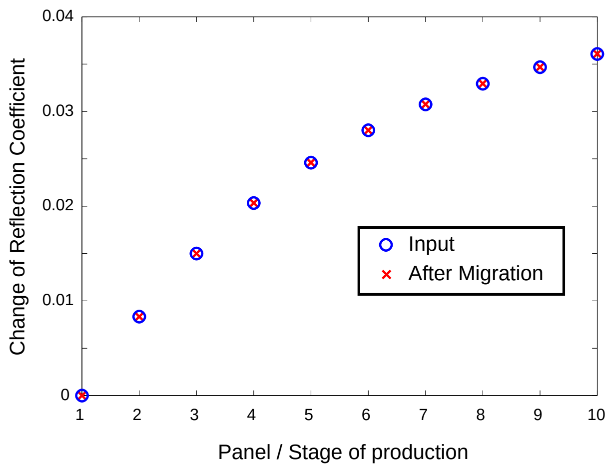


Figure 11: Picked peak amplitudes (crosses) of the target reflector at $x = 2.7$ km for all migrated difference sections. Theoretical values are shown as circles. The amplitudes correctly represent the changes in the reservoir.

CONCLUSIONS

We have shortly presented the theory of modeling by demigration and its relationship to forward modeling. Although both operations produce similar time sections, they are not identical. However, from our considerations we were able to outline the steps which are necessary to use demigration for modeling purposes. Using a simple model with one reflector we have shown that modeling by demigration is able to produce kinematically and dynamically correct images. It is, however, to be kept in mind that the amplitude behavior is smoothed (compared to standard ray tracing results) using modeling by demigration.

Finally, we presented an application of modeling by demigration: the simulation of time-lapse seismics. Reservoir perturbations were investigated by means of simulating synthetic seismograms, calculating seismic difference sections in the time domain, and subsequently migrating the difference sections to depth. In the depth domain, we were able to quantitatively recover the simulated changes in the reservoir. This points out that the *Unified Approach Theory* merges the processes of migration and demigration into one class of target-oriented seismic reflection imaging operations. Due to its origin, “modeling by demigration” readily integrates into this class and can be seen as a link between forward modeling and imaging techniques.

PUBLICATIONS

The application of modeling by true-amplitude Kirchhoff demigration for time-lapse seismics was presented by Riede et al. (2000b, 2001). Detailed results concerning true-amplitude migration and demigration in 2.5D and 3D were published by Riede et al. (2000a), Hertweck et al. (2001a,b), and Jäger (2001).

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