Introduction

In the introduction to these proceedings by Lailly and Versteeg the purpose of the Marmousi workshop was discussed. Especially after many works on seismic imaging in the case of important lateral velocity variations (see the books by Berkhout (1985), Claerbout (1985), Stolt and Benson (1986), Yilmaz (1987) and the paper of Hosken and Deregowski (1985)) it is very interesting to have the results on the Marmousi data set as presented in this volume.

In this synthesis we will now make some observations on different aspects of the results which were (and were not!) obtained in this workshop.

Our article follows the line of the processing; we examine successively the results and limits of

- preprocessing
- standard processing (DMO and stack)
- methods to determine a velocity model by optimization of criteria on prestack information.

After this we examine the ways in which the geological information has been used at the different stages of processing and interpretation and we discuss the general problem of introducing geological hypotheses.

Finally we summarize our conclusions and look towards the future.

Let us emphasize that we are only concerned here with the Marmousi experience which is based on synthetic 2D noise-free acoustic data, and that we leave it to the reader to determine how applicable our conclusions are to the real world.

Preprocessing

Preprocessing (wavelet extraction, deconvolution etc.) is very important. As shown by Elf the consequences of errors at this stage can be disastrous. There is a good consensus on what kind of preprocessing should be done in not-very-complex situations of marine acquisition. Marmousi is such a situation in which it is also possible, owing to the wells on the line, to have a reliable estimate of the wavelet and of the effects of source and receiver patterns.

The participants obtained results which agree quite well on this part but problems remain arising from the variation in the reflection coefficient at the water bottom and from the complexity of the multiple reflections.

Standard processing as a help to obtain a good model

In situations that are not very complex there is a consensus on the benefits of DMO and classical techniques for velocity analysis. It is interesting to note that even in the complex situation of Marmousi the velocities obtained by classical techniques give
a good starting point for subsequent depth migration techniques. This is shown by the two groups who spent efforts in getting a good stack (Prakla and Elf). They obtained interesting results which were of use in the later stage of prestack depth migration. Still the complex situation and the very strong lateral velocity variations do reduce the significance of the hyperbolic stack and three groups (CGG, Delft University and Conoco) seem not to have used the traditional stack but to have directly analyzed depth-migrated gathers to obtain velocity models. Standard processing of course also includes using the stacking velocities (or better a fraction thereof) to time-migrate the section, after DMO and stack. Is this technique useful in the complex case of Marmousi? In fact, there is still meaning in it, as is shown by the results of Elf and Prakla: zero-offset time-migrated sections appear even in this case to be useful tools to start the interpretive process. The events that stack well and migrate significantly will be good candidates, even if not very strong in amplitudes, for starting the coherency analysis procedure.

**Criterion optimization for the velocity model determination**

**Introduction**

The major part of the work done by the participants consisted in determining a velocity model for prestack depth migration using some criterion based on prestack information. In this section we look at the different criteria, we examine their relevancy to the Marmousi case, and we analyze their adequacy for reaching the ultimate goal: the correct velocity field (and from this the correct subsurface image).

**Criteria used for the velocity model determination**

Basically, three criteria were used by the participants:

I Kinematical coherence of the migrated images

This criterion, which has been used by many authors (see for instance Al-Yahya (1987) and van Trier (1990)) relies on the observation that, using the exact velocity model, the migrated images should be (kinematically) identical from one shot point to another (in the case of shot record migration) or from one offset to another (in the case of common-offset migration). For the workshop, this criterion has been used on common-shot migrated images by Elf, Delft Geophysical and Rice University and on common-offset migrated images by Prakla and Conoco.

II Migration focusing time

This criterion has also been used by many authors (see for instance Yilmaz and Chambers (1984) and Jeannot et al. (1986) ) It claims that the best velocity model is the one that provides focusing during the prestack depth migration at a time as close as possible to zero. This principle has been applied to the Marmousi data by CGG, Delft University and Delft Geophysical.

III Prestack waveform match

The waveform match is a very natural criterion which is the basis of inversion by least squares data fitting: it consists in finding the model which gives the best match between synthetic and recorded data. It has been used for a long time to solve 1D problems (Bamberger et al. 1979), (Kolb et al. 1986) and is nowadays also used for 2D problems (Gauthier et al. 1986), (Crase et al. 1990). The prestack waveform inversion was the approach chosen by Rice University (in connection with the kinematical coherence of the migrated images) and by the Institut de Physique de Globe de Paris.

We now examine three key questions concerning these criteria:

- Relevancy
- Sensitivity
- Optimizability

For this discussion we will use and analyze migration results obtained at IFP from the deconvolved Marmousi data (for this the data deconvolved by Elf were used). The migration algorithm we used is shot record migration by a finite difference solution of the 65 degree one-way wave equation.

**Relevancy of the criteria**

Questioning the relevancy of the criteria comes down to asking: would the exact model have
matched the considered criterion for the Marmousi data?

Regarding this we can make the following observations:

I. For the criterion of kinematical coherence, the answer to the question is affirmative if the migrated images show reflectors which can be interpreted as geological events and tracked across different offsets (in common-offset migration) or different shot-points (in shot-record migration). Figure 1 (see also fig. 9 in the paper by Delft Geophysical) shows that checking the kinematical coherence is difficult when the exact velocity model is used. It can be seen that the discontinuities in the exact model create complicated high-frequency events and discontinuities (fig. 2) in the common-shot migrated images. This leads to difficulties for tracking reflectors from one shot point to another. Concerning this, we have noted that if we use a lightly smoothed version of the exact model (colour figure 11) it gives a perfect migrated image (fig. 3, obtained by a stack of the migrated shot-records) in the sense that it is identical to the image obtained with the exact velocity model. However, the events in the migrated shot gathers can be tracked with less difficulty (fig. 4) than in the images obtained with the exact model (fig. 2). With such a smooth model, the kinematical coherence (fig. 5) is as satisfactory as with the exact model and verifying this on the coherency panels is somewhat easier.

As mentioned, the required interpretation step for the criterion of kinematical coherence (identifying and tracking the reflectors across different offsets/shot-points) is not obvious. As we shall show in the section on the use of geologic information this step should be driven by geological arguments.

II. For the criterion on migration focusing time, the results from Delft Geophysical and CGG show that the exact model does not provide exact focusing. This is due to the effect of spurious events. Identification of the exact model thus hinges on the ability of the interpreter to discriminate between real and spurious events, which is far from obvious. We have noted that these spurious events are still present (fig. 6) when the lightly smoothed version of the exact model (colour figure 11) is used to migrate the data.

III. For the prestack waveform match criterion, it is clear that the exact model will match the criterion. Once again we want to stress that we discuss only the Marmousi case. In the case of noisy data we are faced with the important problem of stability with respect to noise which is not discussed here.

Sensitivity of the criteria: ultimate limits of kinematics

We can ask: are there erroneous velocity models that give a wrong image of the structure while matching the criterion?

If the answer is yes then the seismic data do not suffice to find the correct image of the structure: either there are not enough data (e.g. not enough offsets) or the criterion is not adequate (e.g. it may be lacking sensitivity).

It is hard to give a definite answer to this question but we show here (after Geoltrain and Versteeg (1991)) that the criterion of kinematical coherence allows the differentiation between the lightly smoothed version of the exact velocity model (colour figure 11) and another, medium smoothed, version (colour figure 12).

The model shown in colour figure 12 turns out to give an almost perfect migrated image (fig. 7). The associated coherency panels (fig. 8) show that even for such a good model the criterion of kinematical coherence is not matched as satisfactorily as before. In other words: it seems that this criterion is sufficiently sensitive (under the earlier mentioned reservations about interpreting common-shot or common-offset migrated images) for the considered range of offsets.

The limits of the kinematical approach are thus beyond the results given by the participants: the seismic information is sufficient to find a good velocity model, i.e. a model which gives a correct migrated image. This is true at least in this case where many interfaces with different dips and similar reflection coefficients offer a lot of useful data for the tomographic procedure.

The participants could thus have found the correct velocity model, if they had succeeded in the construction of a series of models step by step improving the initial model with respect to the chosen criterion.
Figure 1. Coherency panels (i.e. slice through the cube of migrated shot records at one common surface location) at X=5000 m (top), X=6000 m (middle), and X=7000 m (bottom) for the exact velocity model (colour figure 2).
Figure 2. Shot-migrated images for shots at X=5000 m (top), X=6000 m (middle), and X=7000 m (bottom) for the exact velocity model (colour figure 2).
Figure 3. Stack of the migrated shot gathers using the lightly smoothed velocity model shown in colour figure 11.
Figure 4. Shot migrated images at shot locations $X=5000$ m (top), $X=6000$ m (middle), $X=7000$ m (bottom) for the lightly smoothed velocity model shown in colour figure 11.
Figure 5. Coherency panels at CSLs $X=5000$ m (top), $X=6000$ m (middle), $X=7000$ m (bottom) for the lightly smoothed velocity model shown in colour figure 1.
Figure 6. Focusing panels at CSLs X=5000 m (top), X=6000 m (middle), X=7000 m (bottom), (courtesy of F. Audebert, CGG) for the lightly smoothed velocity model shown in colour figure 11. These focusing panels are to be compared with fig. 8 in the paper by Audebert in this volume.
Figure 8. Coherency panels at CLSs $X=5000$ m (top), $X=6000$ m (middle), $X=7000$ m (bottom), for the medium smoothed velocity model shown in colour figure 12.
Despite the previously mentioned imperfections of some of these criteria, figure 11 in the paper by Elf and figures 10 and 11 in the paper by CGG show the progress which remained to be done.

Difficulties for optimizing the criteria
We divide the analysis into two parts:

- optimization of the focusing time or kinematic coherence criteria, attempted manually by the participants
- optimization of the prestack waveform match criterion by gradient techniques.

Focusing time and kinematic coherence criteria
The results obtained by the participants show that the quality of the focusing or coherence analyses degrades progressively from top to bottom. While there is no doubt that their analyses worked acceptably well to image the shallow part of the model, there is also no doubt that they were not sufficiently accurate to image the deeper part. As a result the images of the more interesting deeper layers were deformed beyond recognition.

The reasons why the quality of the velocity analysis degraded with depth are the inability (as mentioned before) of the participants to separate real from false focusing or to interpret correctly the common-shot or common-offset migrated images, inadequate parameterization (discussed farther on in this article), and difficulties of matching the criterion by hand which we will analyze now.

As a result of the complexity of the wave propagation, one point of the velocity model influences a large region of the migrated image. The participants have very often created velocity updates yielding a better match at specific CSLs (Common Surface Locations) and a worse match at other CSLs. They were not able to find an update yielding a globally better match. And, of course, to obtain a good velocity model one should use algorithms that optimize globally the chosen criterion.

In the case of focusing analysis, it appears that one needs a broader view than that allowed by the focusing panels; the observation of the lateral continuity and congruence of the events might help.

Even if the optimization must be global, let us note meanwhile that it is not suitable to try to match a criterion for the deep events when the criterion is not sufficiently matched for the shallow events. Unfortunately, it may be very hard to evaluate whether a criterion is sufficiently matched.

Prestack waveform match criteria
Concerning waveform inversion techniques, we observe that they were not ready at the moment of the workshop. Besides, these techniques have met great problems even in the case of simple structures as the gradient, i.e. the technique to update the velocity field, is inefficient.

Additionally, compared to the kinematic approach, waveform inversion suffers from its poor ability to detect a weak interface which would be obvious to an interpreter.

On the other side the imagination of the researchers is big (see for instance the work of Symes and Carazzone (1991) which combines waveform match and coherency ending up with a much smoother objective function).

We can thus ask ourselves whether a blind automatic algorithm has more chance of success than a kinematic algorithm guided by the experience of the interpreter, himself not blind even during a blind test! Who knows??

Use of geologic information
Introducing geologic information into the processing is very useful for the following purposes:

- to reduce the model space to be explored and to better constrain the models. Specific parameterizations are often used for that purpose
- to drive the optimization by introducing the interpreter's knowledge through the identification of reflections. The kinematic approach relies on this identification
- to force the optimization to converge towards the solution by guessing it from a geological assumption which has to be checked a posteriori. This is the "trial and error" approach.
Review of geological information used

The geological information at the disposal of the participants is described in the article by Bourgeois et al. (this volume). As noted there, two errors had slipped into this description: the interchange of the numbering of the lithologic logs (the corresponding velocity and density logs were correctly numbered), and the interchange of east and west.

From the geological description two participants (Conoco and Elf) assumed that the base of the salt was flat (which was correct) and that there existed a salt dome (which was not correct). They then went on trying to find the best model satisfying this hypothesis.

CGG made the assumption that the faults were not growth faults, but faults caused by the salt dome rise, while Delft University initially constructed a model based on the hypothesis that the main growth fault dipped west (due to the error in the description).

So all hypotheses considered were partially false and partially true. This is of course a quite general situation, but it makes us consider the construction of hypotheses. This should be done in such a way that there consists a hierarchy of hypotheses.

Hierarchy of geological hypotheses

To progress in structural imaging a large number of hypotheses have to be tested. Obviously, only a small number of these hypotheses will be correct and a problem is how to determine them. The key to constructively testing hypotheses is the use of a treelike hierarchy of hypotheses. This means that one hypothesis will be built on (or contain) another one.

So if we can establish this hierarchy we can then start by verifying the root hypotheses and work our way up. This has the advantage that every time we eliminate a hypothesis all its descendants are automatically eliminated. Another advantage of this approach is that all hypotheses will be explicitly stated so that each assumption will be questioned.

An example of this approach and a discussion on how hypotheses should be tested is given in the following section.

Test of hypotheses — use of the time domain

An example of the hierarchy of hypotheses is: can we test a velocity model to see whether it flattens the base of the salt without having previously confirmed the interpretation of the seismic event considered to be the base of the salt?

The answer is obviously no: the first hypothesis which is to be confirmed is the identification of the seismic event. Only after this can we proceed with the construction of a velocity model with the aim of flattening the base of the salt.

To us this essential validation seems to be necessary before any improvement of the velocity model can be obtained in this case. Having picked in the depth domain the supposed base of the salt and knowing the velocity model (the one being used for the depth migration), it is easy to know the arrival time corresponding to the supposed base of the salt. After this, the comparison of the arrival times with the visible events in the near-offset section should enable the rejection of the hypothesis and the formulation of other ones. An essential step is thus the detailed interpretation of the time image, which is a classical approach of the interpreter.

More generally, we want to test hypotheses on the velocity model that aim at satisfying geometrical criteria of the structural model. This can only be reasonably done after the geological interpretation of the seismic events is validated. This interpretation must be done in the time domain and thus the time-migrated section, which is relatively insensitive to the velocity model, is essential for this part.

Let us note here once again the usefulness of the time-migrated image (see fig. 4c of the Conoco paper and fig. 8 of the Prakla paper): it is much easier to interpret than the unmigrated sections. These migrated images show the principal characteristics of the depth images obtained by the participants. Notably the flanks of the deep anticlinal structure can be seen; obviously the associated reflections propagate in a simple way for the small offsets and will appear clearly in the time-migrated section. The migrated time section thus seems to be crucial for the interpretation of the seismic events and
verification of hypotheses necessitates an extensive use of the time domain.

Parameterization of the model

The basic underlying hypothesis for the velocity models used by the participants was that of major continuous interfaces separating layers characterized by gentle lateral variations of velocities. Strong velocity changes were only allowed from one layer to another.

This hypothesis is indeed valid in many cases of interest to the oil industry. However the presence of the high-velocity blocks in the shallow middle part of the Marmousi model, creating abrupt velocity changes along the horizontal axis, was in conflict with this approach.

In spite of this conflict, Elf and Prakla who worked with rather smooth velocity models obtained a reasonable image of the deepest part of the structure: it thus seems that using smooth velocity models is an acceptable approach even in the Marmousi case. On the other hand, a layered model is more "geological" and it is quite natural and tempting to introduce geological hypotheses and information via the parameterization: this constrains the model we look for, limits the number of parameters and permits an easier manual update of the velocity model.

Nevertheless this approach seems very dangerous if the "real" model does not belong to the class of parameterized models as the non parameterized part of the "real" model may contain components to which the criterion we want to optimize is very sensitive.

This is the case for the models parameterized by the participants which are too simple to take into account all the complexity of Marmousi. In particular the lateral velocity variations in the Marmousi model that have a very important effect on the propagation do not appear in the parameterized models. The correct diagnosis was formulated by Conoco: "The data can be correctly migrated only when the high-velocity faulted blocks above the turtleback are correctly included in the model. At the same time these pieces are small and deep enough to make it very difficult for any velocity analysis to handle them".

In conclusion, the parameterization of the velocity model must contain all the components of the velocity model to which the criteria are sensitive (see Versteeg (1990) and Geoltrain and Versteeg (1991) for an estimate of these components). The geological information (being inherently vague) should not be introduced in a rigid way through the parameterization but in a flexible way (which still remains to be found).

The trial and error approach

The trial and error approach was necessary because of the difficulties met at some stage for finding a good update of the model just from geophysical considerations.

Unhappily enough the hypotheses which were tested were all found to be wrong and it has not been possible to eliminate them on geophysical criteria. This is mainly due to the difficulties to interpret physically the effect of hypotheses tested on the mismatch of the chosen criterion.

The only guide was thus the aspect of the migrated image (we noted "the lure of the sharper looking wavelet" mentioned by Conoco) and its ability to evoke a preconceived geological structure: this guide has not sufficed for the elimination of the hypotheses tested, and the participants seem to have proceeded blindly.

We think it important to underline the crudeness of the approach taken and the consequent risk of entrapment.

The cause of the problems with the trial and error approach is twofold:

- it's hard to test one hypothesis independently from others
- the hypothesis being described by a model, the test of a hypothesis demands the test of a large number of models. And even so, can we really abandon a hypothesis when we have put aside a large number of models which represent it?

Clearly there is thus still a lot of progress to be made in making the trial and error approach an effective one.

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Conclusions

What did we learn from the Marmousi workshop? First of all, we learned that no one was able to produce a good image of the Marmousi model from the data: we have not been able to solve a 2D noise-free acoustic problem. Basically the participants have used incorrect hypotheses resulting in an imperfect reconstruction of the image. The results of these hypotheses (incoherent images, absurd velocities) should have been analyzed, leading to new and better hypotheses.

This is the kind of conclusion which is easy to write when we know the solution. But we can not forget that only a limited amount of real manpower can be spent on a synthetic model.

We do not complain therefore that the solution was not found: we find it satisfying that all found, in the post workshop analysis and in the reconsideration of their processing, elements that could have led to a reevaluation of the case, and maybe to a correct solution, given more time and resources.

And, we are on the right road to find a solution: coupling of the results of the participants would have given a much better image than those independently produced by the participants. For instance, putting together the results of Prakla and Conoco would lead to a significant improvement of the model, and thus of the image quality.

We conclude from this experiment that the key elements for obtaining a better solution are

- ability to extract a good source wavelet
- correct interpretation of conventional processing results; identification of major reflectors in the time domain, even if the tracking of deep events is difficult
- updating the velocity model by matching a criterion based on prestack information, coupled with the ability to interpret the criterion mismatch
- an adequate parameterization of the velocity model
- ability to introduce and test geological hypotheses.

The ability to interpret a criterion, thus to separate real and spurious events, and thus to proceed in the right direction while updating the model is essential.

The future

The participants all said to have learned a lot from this blind test. Researchers continue to work with this data set and will continue to learn a lot from it. Of course the data are 2D acoustic, and we can be accused of being non realistic, but 2D acoustic seems to be far from trivial at the moment (for the complexity of Marmousi). Still, it would of course be very interesting to have at our disposal a 3D realistic experiment.

The need for such a 3D realistic experiment was formulated during the workshop and we studied this exciting idea. Of course such a 3D project will be gigantic, not only regarding computer time required, but even more in the definition of a realistic 3D geologic model.

For this reason, and regarding the very wide interest of such a 3D data set we made a proposal for a joint EAEG/SEG project to take on this tremendous challenge.

There is no doubt that, if the geophysical community wants to do it, a kind of 3D Marmousi can be available within 5 years from now. There is also no doubt that the increase in value when going from 2D to 3D Marmousi will be worth and exceed the increase in expense.

Acknowledgements

We thank Elf for providing us with the deconvolved data, François Audebert (CGG) for making available figure 6, Sébastien Geoltrain and Andreas Ehinger for the figures of migration coherency panels and for their analysis of the results.
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