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# Structural-velocity estimation – imaging salt structures

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## ABSTRACT

Depth migration is often needed for the correct imaging of salt structures. However, the velocity model necessary for the migration is hard to determine in salt regions, because of large lateral velocity variations and poor data quality. In previous reports I discussed a gradient optimization method to estimate a structural-velocity model in these regions. The method is based on the inversion of perturbations in prestack migrated events, where the events correspond to structural boundaries picked from the migrated image. The optimization does not require picking of prestack data; the data part of the gradient is determined from local semblance calculations. A preliminary analysis of a dataset recorded above a salt structure explores the difficulties in salt imaging, and illustrates the gradient calculation.


## INTRODUCTION

Although many migration algorithms are now capable of accurately imaging seismic data, imaging near salt structures remains a hard problem to solve. Complications in the imaging arise for several reasons. First, because of the high-velocity salt intrusion, velocity generally varies strongly, both in depth and laterally. Reflection events are therefore non-hyperbolic, and time migration does not produce satisfactory results. Instead, depth migration is needed, not only for focusing the data, but also for correctly locating salt boundaries (Larner, 1987). Second, data quality can often be poor in salt regions. The intrusive salt flow breaks up sediments above and alongside the structure, and these broken-up sediments do not generate clear reflections. Third, because of the high reflection coefficient of salt-sediment contrasts, little seismic energy penetrates the salt structure, and reflections from sediments below the salt are weak.

In previous reports (Van Trier, 1988; Van Trier, 1989a) I discussed a method to try to solve the first problem, the depth-migration and its related velocity-estimation

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problem – the second and third problem are mostly data acquisition problems. The velocity-estimation method determines structural velocities using migrated seismic data. After migration with an initial velocity model, structural boundaries are picked from the migrated image. The residual perturbations in the prestack migrated events that correspond to the picked reflectors are then used to optimize the velocity model. The optimization method is a gradient method, where the goal is to maximize semblance in the stacked migrated image. The gradient calculations in the optimization consist of two parts: a tomographic part that is calculated using ray tracing, and a data part that calculates semblance derivatives in the prestack migrated data.

In the last report I concentrated on the ray-tracing part; in this report I discuss the data gradient. I first show a data example that was recorded over a salt layer. Then I discuss some of the issues in applying the calculation to salt data, and, finally, I describe the data-gradient calculations in detail.

## FIELD DATA EXAMPLE

This section describes an exploratory study of a marine dataset recorded over a salt structure. The dataset is from Conoco, and was donated to SEP by Western Geophysical Co. that did most of the preprocessing. It contains 239 shots, each consisting of 84 geophones. The geophone spacing equals the shot spacing, and is 30 m. The near-offset distance is 75 m. The time sampling interval is 4 ms, the total time 3 s.

Figure **??** shows two shot gathers, Figure **??** displays two CMP gathers at about the same location. The reflections at 1.3 s and 1.8 s are reflections from the top and bottom of a salt layer. The extent of the salt structure is shown on the near-offset (Figure **??**) and stacked section (Figure **??**). The velocity function used for the stack is displayed in Figure **??**.

The top and bottom of the salt are reasonably well-defined in the left and right part of the section, but do not show up clearly in the middle part. The salt has flowed upward in this middle part, bending and faulting the sediments above it. These warped sediments cause lateral velocity variations, which become even more pronounced below the salt layer because of variable salt thickness. The moveout of the reflection events is therefore non-hyperbolic as can be seen in Figure **??**, and stacking-velocity analysis breaks down.

Figures **??** and **??** show the result of such a velocity analysis at two midpoints. The salt top reflection is mostly hyperbolic in the left part of the section (the semblance peak at 1.2 s in Figure **??** is well-defined), whereas the reflection becomes non-hyperbolic at the dome: different parts of the moveout curve stack in at different velocities, broadening the semblance peaks in the velocity panels. The non-hyperbolicity is caused by lateral velocity variations in the bended sediments above the dome, and probably also by discontinuities in the salt top. The salt bottom reflection is much less apparent in the velocity analysis; not only do lateral velocity variations distort the moveout of this reflection, but it is also much weaker: the high reflection coefficient at the salt boundary prevents seismic energy from penetrating the salt structure.

### Migration

Figure **??** shows the migrated image after prestack depth migration. In this example I have concentrated on imaging only the sediments and the top of the salt, which already turns out to be a complicated task.

For the migration I have used a velocity function that changes linearly with depth, with the exception of a constant-velocity layer at the top (Figure **??**). The model is constant in the lateral direction. In reality, the velocity is rapidly changing with surface position, and the migration has done a poor job in imaging the subsurface. This is apparent from several features in the stack. First, coherency in the stack deteriorates below surface positions ranging from about 2 to 3.5 km, which is caused by a low velocity channel at the top of the section. Second, the frequencies in the stack are lower than in prestack migrated data (see Figures **??** and **??**): velocity effects cause large residual moveout that smears events when they are stacked. Finally, the top of the salt layer does not stack in into the image, but does show up in the prestack migrated constant-offset sections (at a depth of about 1.25 km on the left part of the section, and about 1.5 km on the right in Figures **??** and **??**). The same applies to the fault plane reflections. Although the velocity model is far from correct, the result suffices for the purpose of analyzing the migrated data.

The migration method is a Kirchhoff method, where I calculate Green's functions using finite-difference calculations (Van Trier, 1989b). A Kirchhoff method allows partial imaging of the subsurface, which is useful if only major events in the data need to be migrated (see later section). Although the stacked result stays the same, the prestack migrated data can be organized in different ways, such as migrated shot profiles or migrated constant-offset sections. The advantage of constant-offset migration is that these sections resemble the geology, and are individually interpretable. This is an important feature as will become clear later.

Examples of partial stacks of migrated constant-offset sections are shown for two different offsets in Figures **??** and **??**. These sections display more detail than the stacked image. In particular the salt top is apparent in the section, although its exact shape at the peak of the intrusion is not distinguishable. The migrated data also reveal the dipping part of the salt top on the right, which is not visible in the stacked section (Figure **??**). Not enough depths are included in the migration to image the salt bottom on the right. Finally, note the events below the low velocity channel on the left; these events have almost completely disappeared in the stacked image.

Figures **??** and **??** display slices through the prestack migrated data at various surface locations. If the correct migration-velocity would have been used, all the events in these panels would have been flat. Most of the events have been overcorrected, meaning that the migration velocity is too low. At the outer parts of the section the residual moveout is reasonably well-behaved, but in the middle part, above the salt dome, the residual moveout suggests considerable lateral velocity variations.

## VELOCITY INFORMATION FROM MIGRATED DATA

Strong lateral velocity variations occur in salt regions, which result into non-hyperbolic moveout of reflection events. Velocity-estimation methods that use stacking or other coherency measures calculated over the whole cable length may therefore not resolve local perturbations in the moveout of reflection events. While having higher resolution, tomographic methods that use picked traveltimes cannot easily be applied to salt data because of the mentioned data quality problem.

Migrating the data partially solves the velocity problem: by incorporating lateral variations in the migration velocity, the velocity-estimation method only has to back-project residual moveout. However, as was shown in Figure **??**, the residual moveout pattern can still be complex in salt data. Therefore, I use a local stacking operator for the gradient calculations in the optimization, and I constrain the velocity model by an interactive interpretation of the migrated image. The next two sections discuss these procedures in detail.

### Gradient calculation

In SEP-60 I discussed an optimization method that backprojects perturbations in prestack migrated events onto the velocity model. In general, the perturbations are not readily available; picking them on the constant surface location gathers is cumbersome and not very reliable for the data shown here. However, it may be feasible to pick events from the migrated constant-offset sections after they have been locally stacked to reduce noise. The sections resemble the geology, at least for the inner offsets, as can be seen in Figure **??** and **??**.

A method that avoids picking altogether uses semblance derivatives, and was described in my previous report. Semblance in the stacked image is calculated along stacking trajectories in the prestack migrated data. Instead of picking perturbations in the stacking trajectory, semblance derivatives along the trajectory drive the optimization method. I briefly review the calculations here; for more details I refer the reader to the SEP-60.

The derivative of semblance $J$ with respect to $z_m$ for a certain event is:

$$\frac{\partial J}{\partial z_m}(\mathbf{S}, h) \;=\; \frac{J(\mathbf{S}_{+\Delta z}(h)) \;-\; J(\mathbf{S}_{-\Delta z}(h))}{2\Delta z}, \tag{1}$$

where $h$ is offset, and $(x_m, z_m)$ the position after migration. $\mathbf{S}$ is the current stacking trajectory, and $\mathbf{S}_{+\Delta z}$ and $\mathbf{S}_{-\Delta z}$ are perturbations thereof. $\mathbf{S}_{+\Delta z}(h)$ is the upward perturbed trajectory; it is the same as $\mathbf{S}$, except for a perturbation by $+\Delta z$ in the $z_m$ direction at offset $h$:

$$\mathbf{S}_{+\Delta z}(h) \;=\; \begin{cases} (x_m(h), z_m(h) + \Delta z, h) & \text{at offset } h, \\ \mathbf{S} & \text{elsewhere.} \end{cases} \tag{2}$$

Likewise, $\mathbf{S}_{-\Delta z}(h)$ is perturbed by $-\Delta z$ at offset $h$.

The gradient calculation is not very robust if the trajectory is just shifted at one offset, as described in the above equation. Therefore, the path is perturbed at several offsets, with the perturbations decreasing away from the offset under consideration. This is schematically illustrated in Figure **??**.

### Structural analysis

Since salt has a high-velocity contrast with respect to the surrounding sediments, and accurate positioning of salt boundaries is crucial for oil exploration, it is important to find a structural velocity model in the velocity analysis, rather than one that just focuses the migrated data. Also, constraining the velocity model by an (interactive) structural interpretation of the image reduces the model null space in the inversion, and thus speeds up the optimization.

Therefore, I construct a structural model from the migrated image and limit the optimization to the events in the data that correspond to the major structural boundaries. This significantly reduces the amount of data in the optimization, and allows me to do prestack migrations at little cost in different iterations in the migration. Kirchhoff migration is well-suited for migrating limited amounts of data to certain target regions. The targets here are windows around the boundaries: if the model is updated, a simple event migration determines the position of the updated boundaries, and Kirchhoff imaging only has to be done for gates around the updated depth positions of the boundaries.

The constantly changing positions of the windows in the prestack depth-migrated data can be problematic in the optimization. A possible solution is to do zero-offset modeling of the migrated constant-offset sections; the depth axis then gets converted to a pseudo-depth axis, and the zero-offset section stays constant. The converted data is the same as DMO-corrected data, where the DMO correction is calculated for a arbitrary velocity medium (Popovici and Biondi, 1989).

This conversion also has some advantages for the optimization itself: the back-projection operator does not have to take movements of the zero-offset section into account, but instead concentrates on the non-zero-offset behavior of the reflections events – the part that provides the most velocity information. I discussed this matter in more detail in my previous report (Van Trier, 1989a). Figure **??** and **??** show the result of zero-offset modeling the migrated constant-offset sections; the plots show a constant offset and constant surface location slices through the converted data, respectively. A disadvantage of this data representation is that time sections are harder to interpret for complex structure. It is hard to decide which data representation is the most convenient in velocity analysis without actually applying the velocity inversion; I will investigate this in the near future.

## CONCLUSIONS

In previous reports I have presented a method to analyze prestack migrated data that can be used in a structural-velocity optimization. The method relies on a structural interpretation of the migrated image, and does not require picking of prestack migrated data. In this report I have shown an example of salt data, the type of data that I intend to apply my method to. Several conclusions can be drawn from the results presented here. First, a structural analysis is necessary to geologically constrain the velocity model. Salt regions have complex structure, and automated velocity-estimation methods often fail without the help of interactive interpretation of the inversion results. Second, even though migrating the data with a 2-dimensional velocity model reduces the effects of lateral velocity variation on the data, the residual moveout in the data can be complicated. Therefore, local effects in the residual moveout curves have to be taken into account in the velocity estimation to determine correctly the structural model.

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