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Short Note

Wave-equation MVA applied to 4-D seismic monitoring

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INTRODUCTION

4-D seismic processing is gradually maturing as a technique able to aid time lapse monitoring of seismic reservoirs (Lumley, 1995; Biondi et al., 1996). However, many limitations hamper the ability of 4-D seismic monitoring to produce reliable results in complicated reservoir situations. One such example is that of multi-layer reservoirs where changes at deeper levels are masked by those that occur at the top reservoir. In these cases, only the top-most reservoir is analyzed and changes at the deeper levels are disregarded or at least treated as suspect.

Of particular interest is the case of reservoirs where the pressure configuration is such that gas is at the limit of release in solution (Kristiansen et al., 2000). Any drop in pressure, likely to occur during production, leads to gas release which results in substantial change in velocity. In these cases, the 4-D effects are mainly driven by the changes in acoustic velocity. For these reservoirs, 4-D seismic monitoring can be seen as a velocity analysis problem.

Biondi and Sava (1999) introduce a method of migration velocity analysis based on wave-equation techniques (WEMVA) which uses the changes visible in the entire seismic image to infer velocity information. Such a technique is ideally suited to deal with velocity-related 4-D changes observed over entire images, including the case of multi-layer reservoirs.

Traveltime-based MVA methods cannot be easily used to solve this problem for several reasons: the traveltime changes that occur over time are too small to be picked with enough accuracy; amplitude information, although very important, cannot be used and is, therefore, ignored.

WEMVA applied to 4-D problems has limitations as well. First, WEMVA can only handle the image changes due to perturbations of the acoustic velocity since our current implementation is based on the acoustic wave-equation. Second, WEMVA can only handle small velocity anomalies, due to the inherent Born approximation. This, however, is unlikely to be a problem for 4-D analysis since the image changes are smaller than a fraction of the seismic wavelet.

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METHODOLOGY

In its original formulation (Biondi and Sava, 1999), wave-equation migration velocity analysis relates a perturbation of the slowness model ($\Delta\mathbf{S}$) to its corresponding perturbation of the seismic image ($\Delta\mathbf{R}$). Mathematically, this relation can be expressed as the linear fitting goal

$$\mathbf{L}\Delta\mathbf{S} \approx \Delta\mathbf{R}. \tag{1}$$

$\mathbf{L}$ is the WEMVA operator that is constructed as a linearization of downward continuation operators involving the Born approximation (Sava and Fomel, 2002). We obtain the slowness perturbation $\Delta\mathbf{S}$ from Equation (1) by applying either the adjoint or the least-squares inverse of $\mathbf{L}$ to the image perturbation $\Delta\mathbf{R}$.

The critical quantity in Equation (1) is the perturbation of the seismic image $\Delta\mathbf{R}$. For the purpose of this equation, this is the known quantity and various techniques can be used to derive it.

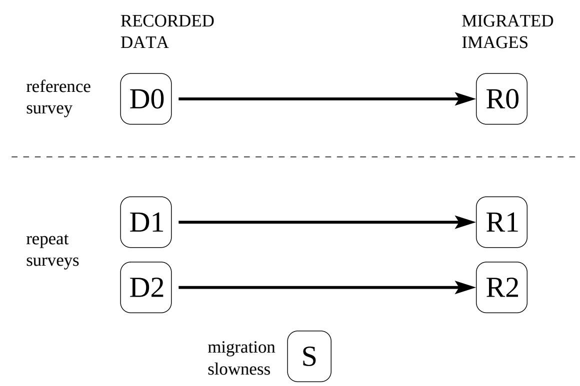

Figure 1: Different 4-D datasets imaged using the same slowness model produce different seismic images, from which we can extract image differences for WEMVA. paul1-4Dscheme [NR]

In 4-D seismic monitoring, the image perturbation is defined as the difference between the images at various acquisition times with respect to the reference image. For example, suppose that at time $t = 0$ we record a reference dataset $\mathbf{D}_0$ which is imaged with the migration slowness $\mathbf{S}$ to produce the reference image $\mathbf{R}_0$. At later times, repeat surveys produce new datasets $\mathbf{D}_1, \mathbf{D}_2 \ldots$ which are different from $\mathbf{D}_0$ and, therefore, reflect the changes in the reservoirs.

After imaging using the same slowness model $\mathbf{S}$, we obtain the images $\mathbf{R}_1, \mathbf{R}_2 \ldots$ which are different from the reference image $\mathbf{R}_0$ (Figure 1). The image differences or perturbations are obtained by simply subtracting the reference image from each of the repeat images. Once we have created the image perturbations $\Delta\mathbf{R}_1, \Delta\mathbf{R}_2 \ldots$, we can invert for slowness perturbation $\Delta\mathbf{S}$ using Equation (1).

EXAMPLE

We illustrate this technique with a synthetic model that resembles a typical producing reservoir in the North Sea. The model is depicted in Figure 2: the reflectivity on the left, and the reference slowness on the right. The model consists of several fractured horizontal reservoirs which are in production. The reference slowness is smooth and not conformant with the stratigraphy. We assume that the reference slowness **S** is derived from the reference survey and that it perfectly focuses the reference data $\mathbf{D}_0$ to create the reference image $\mathbf{R}_0$.

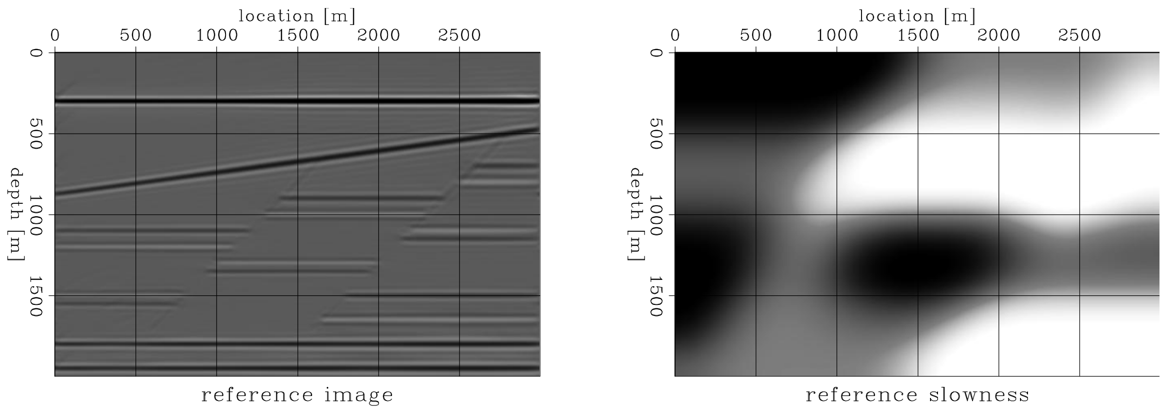

Figure 2: Synthetic model: reflectivity (left) and slowness (right). paul1-model [CR]

Figure 4 shows the slowness perturbations we introduce in the slowness model. For each of the two scenarios, we generate data using the same reflectivity (Figure 2) but different slowness models generated by adding the respective slowness perturbations to the reference slowness. We then image using the reference slowness to create repeat survey images. Finally, we subtract the reference image from each of these two images and obtain the image perturbations (a.k.a. the 4-D seismic data) depicted in Figure 3.

Figure 3 enables us to make two observations:

- Although the changes in the reservoirs occur at only two levels, the changes in the images occur at all levels underneath. This situation is common for 4-D seismic surveys. Typically only the top reservoir can be properly analyzed since the 4-D effects created by the deeper reservoirs are either masked or seriously shadowed by the top reservoir.
- Completely different changes in the reservoirs yield fairly similar perturbations of the images. Even for such a simple model, as the one we use in this analysis, it is really hard to visually analyze the image perturbation and distinguish among the two cases (Figure 3). In practice, this distinction is virtually impossible, and the only place where we can extract reliable information is at the top-most producing reservoir.

We address the ambiguity of the 4-D interpretation using WEMVA. Figure 5 shows the slowness perturbations obtained by the adjoint of the WEMVA operator **L** in Equation (1) applied to the image perturbation $\Delta\mathbf{R}$ in Figure 3. The two cases can be better distinguished now, although the information is not yet localized at the producing reservoirs.

The least-squares inversion result, shown in Figure 6, is much better focused at the reservoirs. Despite the inherent vertical smearing mainly caused by the limited data aperture, we can precisely indicate the location of the producing reservoirs, the sign of the slowness change, and even the relative magnitude of the change from one reservoir to the other.

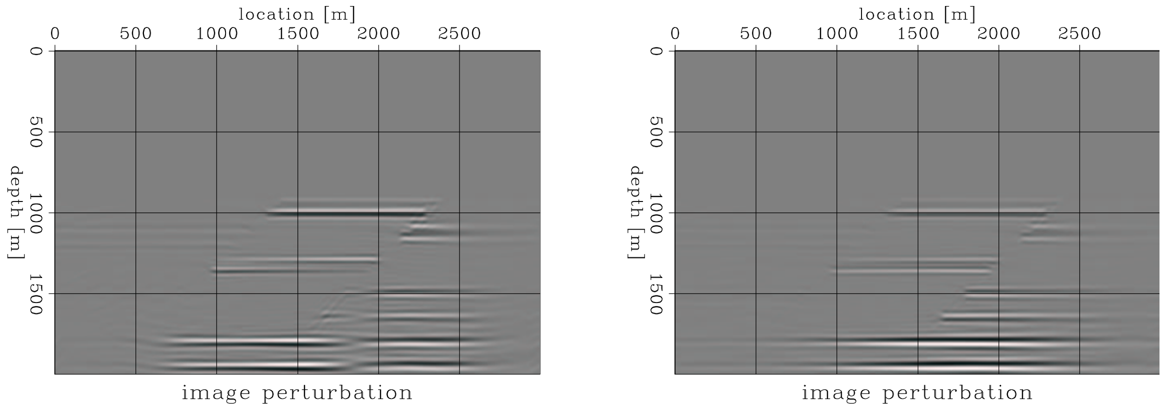

Figure 3: Image perturbation: scenario 1 on the left and scenario 2 on the right. paul1-dimag [CR]

DISCUSSION

The processing method outlined in this paper is mainly applicable to the situations when the 4-D effects translate into significant slowness variations, for example in cases where pressure changes lead to release of gas in solution and consequently to a drop in velocity. Furthermore, the method is strongly dependent on the quality of the recorded data and also on the quality of the 4-D pre-processing.

We must insure that our definition of the image perturbation is mainly a product of the slowness model perturbation. Much care needs to be taken to eliminate all acquisition differences between the repeat surveys and all processing differences of the different datasets. An ideal case consists of fixed acquisition (permanent water-bottom receivers, for example) and identical seismic processing.

Correct handling of amplitude data in migration is as important as in any method addressing reservoir-related properties. However, in this method we are mainly concerned with the differences between repeat images and not as much interested in their absolute magnitude. Therefore, this method is likely to be robust with respect to the accuracy of the more or less accurate migration amplitudes. This particular subject, however, requires careful further analysis.

CONCLUSIONS

We present an application of the WEMVA methodology to 4-D seismic data. If certain physical conditions are met, this velocity analysis method is capable of identifying the producing reservoirs, even for the cases of production from multiple levels.

4-D pre-processing remains an important component of the method. We need to insure that all image perturbations are not related to differences in acquisition and/or processing, but

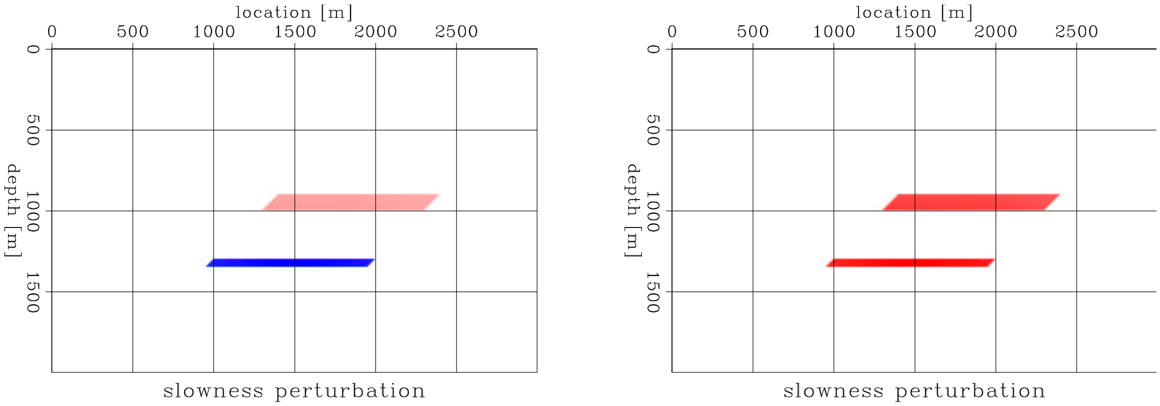

Figure 4: Slowness perturbation: scenario 1 on the left and scenario 2 on the right. paul1-dslow [CR]

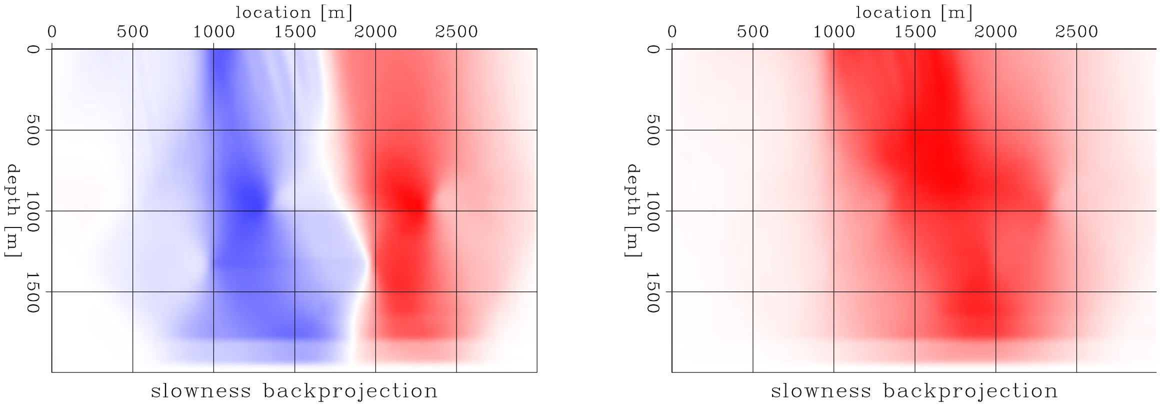

Figure 5: Slowness perturbation obtained using the adjoint of operator **L** in Equation (1). paul1-bslow [CR]

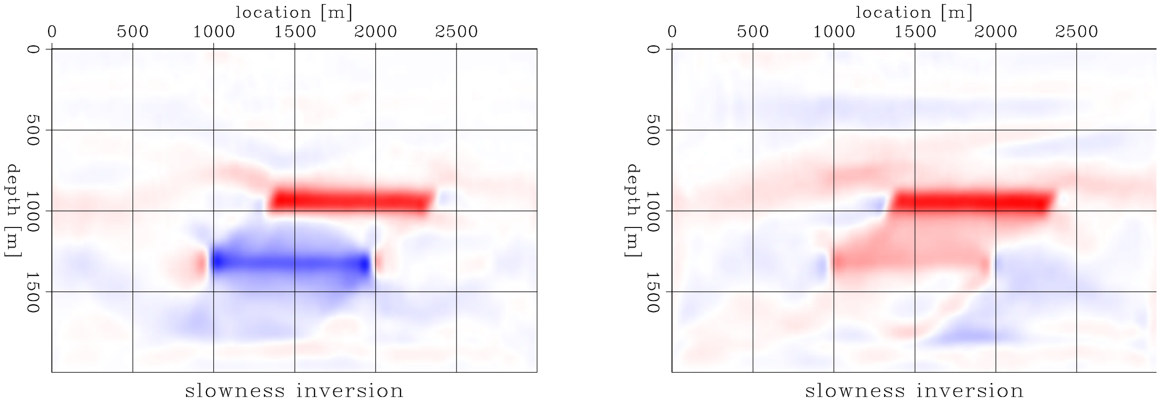

Figure 6: Slowness perturbation obtained using the least-squares inverse of the operator **L** in Equation (1). paul1-islow [CR]

only to changes of the physical parameters of the reservoir. Furthermore, since our processing is purely acoustic, we also need to insure that the image changes are dominated by changes of compressional slowness, and not by other elastic effects.

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