

A proposal for 4-D seismic imaging

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Introduction. Induced changes (e.g. due to exploration activities) in the subsurface geology can be detected if they can be related to a temporal change in the medium parameters. However, this is only true if the time rate of change is happening on a time scale which is much larger than the experiment time of a standard seismic survey. The seismic activity associated with this type of diagnosis is known as 4-D seismics or time-lapse seismics. In the spring of 1996, the chairman and chief executive of Schlumberger, Mr. E. Baird, announced that the productivity of existing oil fields could be boosted from a recovery rate of 35 % to a recovery rate of 50 %. In this context, Mr. Baird (Corzine, 1996) was hinting at an application of the 4-D seismic technology by stating that the key to achieve such gain would be a more accurate seismic image with the ability to monitor in real time the fluid movements within the oil reservoirs. The idea of monitoring this kind of changes originates from Nur et al. (1984) who observed significant changes in the compressional wave speed in cores saturated with heavy oil as a function of the ambient temperature. From this observation he conjectured that seismic techniques could be used to monitor the thermal effect of injected steam to enhance the oil recovery of a reservoir. Today we can confirm that Nur's conjecture is a viable option in reservoir management (Lumley (1995) and Lee (1996)). Not only thermal effects on wave propagation can be monitored. Cruts et al. (1995) showed that induced stress in reservoir rock changes the anisotropy of rock parameters. This study is important for the gas-producing fields in the Northern part of the Netherlands. The hydrostatic pressure drop in the reservoir due to gas production induces the subsidence and triggers small earth quakes. In this case 4-D seismics could be used to forecast the stress build-up in the medium and its geological consequences.

Up to this point the results of the 4-D experiment have been employed to produce a difference dataset from the survey at the start and the one after a certain time span (see for example Lumley (1995)). Then from this difference conclusions are drawn with respect to the medium change. In this paper we show that this difference is related to the restricted area where the changes occur using the reciprocity theorem. Moreover this formulation allows us to connect the two observations in an algorithmic fashion which makes it possible to handle 4-D prestack imaging.

The seismic 4-D formulation. Using the acoustic reciprocity theorem (Fokkema and van den Berg, 1993), where state 0 is connected with a seismic experiment at $t = t_0$ and state 1 relates to a situation at $t = t_1$, and only considering compressibility contrasts ($\Delta\kappa$), the following boundary integral representation is obtained

$$\Delta P(\mathbf{x}^R|\mathbf{x}^S) = \int_{\Sigma_{n-1}^-} \frac{1}{\varrho} \left[\Delta P \partial_k G^0 - G^0 \partial_k \Delta P \right] n_k dA - \int_{\Sigma_n^+} \frac{1}{\varrho} \left[\Delta P \partial_k G^0 - G^0 \partial_k \Delta P \right] n_k dA \quad (1)$$

for $\mathbf{x}^R, \mathbf{x}^S \in \mathbb{D}_n, \quad n = 2, 3, \dots$

where $\Delta P(\mathbf{x}^R|\mathbf{x}^S) = P^1(\mathbf{x}^R|\mathbf{x}^S) - P^0(\mathbf{x}^R|\mathbf{x}^S)$ represents the difference of the acoustic pressure wave fields in both states, $G^0(\mathbf{x}|\mathbf{x}^S)$ is the Green's function in state 0, ϱ is the mass density and \mathbb{D}_n is a contrast free domain, sandwiched between Σ_{n-1}^- and Σ_n^+ (see Figure 1).

4-D redatuming. In the previous section we have given an exact expression for the difference field $\Delta P(\mathbf{x}^R|\mathbf{x}^S)$ in terms of boundary integrals along Σ_{n-1}^- and Σ_n^+ , assuming that \mathbf{x}^R and \mathbf{x}^S are situated in the domain \mathbb{D}_n . Since in practice the measurements are carried out with \mathbf{x}^R and \mathbf{x}^S at or just below the surface, we need a procedure to redatum the data from the surface to virtual acquisition levels in any of the domains \mathbb{D}_n . The main complication is caused by the contrast domains $\mathbb{D}_1^c \dots \mathbb{D}_{n-1}^c$ in which the changes have taken place between the measurement times t_0 and t_1 . Therefore we propose to redatum $P^0(\mathbf{x}^R|\mathbf{x}^S)$ and $P^1(\mathbf{x}^R|\mathbf{x}^S)$ adaptively, thus accounting for the difference of the macro models in the contrast domains $\mathbb{D}_1^c \dots \mathbb{D}_{n-1}^c$. $\Delta P(\mathbf{x}^R|\mathbf{x}^S)$ is obtained by subtracting the results. Using the one-way approach to redatuming (Wapenaar and Berkhout, 1989) means that in equation (1) the integral over boundary

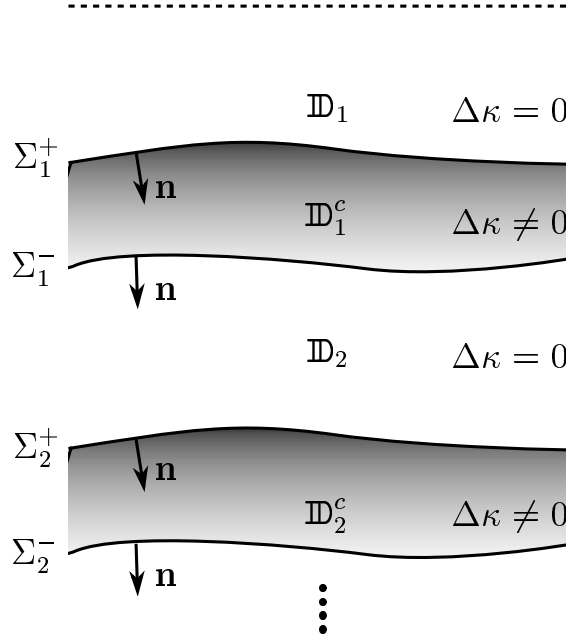


Figure 1: The contrast domains \mathbb{D}_n^c in the 4-D seismic situation.

Σ_{n-1}^- is neglected, leaving

$$\Delta P(\mathbf{x}^R|\mathbf{x}^S) \approx - \int_{\Sigma_n^+} \frac{1}{\ell} \left[\Delta P \partial_k G^0 - G^0 \partial_k \Delta P \right] n_k dA \quad (2)$$

for $\mathbf{x}^R, \mathbf{x}^S \in \mathbb{D}_n, \quad n = 1, 2, \dots$

4-D imaging. Using reciprocity and evaluating the pertaining contributions at the boundary Σ_n^+ , we arrive at

$$\Delta P(\mathbf{x}^R|\mathbf{x}^S) = \int_{\Sigma_n^+} \int_{\Sigma_n^+} \mathbf{W}^T(\mathbf{x}^R|\mathbf{x}') \Delta \mathbf{R}(\mathbf{x}'|\mathbf{x}) \mathbf{W}(\mathbf{x}|\mathbf{x}^S) S(\omega) dA(\mathbf{x}') dA(\mathbf{x}) \quad (3)$$

for $\mathbf{x}^R, \mathbf{x}^S \in \mathbb{D}_n, \quad n = 1, 2, \dots$

where $S(\omega)$ is the spectrum of the source wavelet, $\Delta \mathbf{R}$ is the difference of the reflection operators in both states, according to

$$\Delta \mathbf{R}(\mathbf{x}'|\mathbf{x}) = \mathbf{R}^1(\mathbf{x}'|\mathbf{x}) - \mathbf{R}^0(\mathbf{x}'|\mathbf{x}) \quad (4)$$

and \mathbf{W} is a propagator, defined in terms of the Green's function G^0 . This set of equations constitutes the basis for 4-D prestack imaging of the boundaries Σ_n^+ . Optionally a second redatuming can be carried out via the imaged boundaries, followed by a prestack imaging of the boundaries Σ_n^- .

References

- Corzine, R., 1996, New technology 'to bring boost in oil production': Financial Times, London, April 9.
- Cruts, H. M. A., Groenenboom, J., Duijndam, A. J. W., and Fokkema, J. T., 1995, Experimental verification of stress-induced anisotropy: 65th Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 894–897.
- Fokkema, J. T., and van den Berg, P. M., 1993, Seismic applications of acoustic reciprocity: Elsevier, Amsterdam.
- Lee, D. S., 1996, Integrated seismic study for thermal monitoring: J. Seismic Expl., **5**, 5–18.
- Lumley, D. E., 1995, 4-D seismic monitoring of an active steamflood: 65th Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 203–206.
- Nur, A., Tosaya, C., and V-Thanh, D., 1984, Seismic monitoring of thermal enhanced oil recovery processes: 54th Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 118–121.
- Wapenaar, C. P. A., and Berkhout, A. J., 1989, Elastic wave field extrapolation: Elsevier Amsterdam.