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Time-Lapse Refraction Methods – Status and Future Challenges

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Summary

One of the major challenges that time-lapse seismic will face is the monitoring of carbonate reservoirs. Refraction time-lapse has the potential to overcome this challenge However, there are some challenges which should be met. Some of these opportunities are discussed in this paper. Understanding the amplitude behavior at critical offset and its relation to the maximum amplitude offset is one important challenge. Another challenge is guided waves within the water layer that disturb a clean detection of the refracted events from the reservoir. It is also important to measure at sufficiently large offset as well as using a relatively dense offset sampling in order to detect subtle changes in critical offset. The focus on repeatability will probably continue since it is a common challenge for both conventional and refraction time-lapse seismic.

Introduction

Seismic reservoir monitoring is increasingly accepted as a reservoir management tool (Amundsen and Landrø, 2007). One challenge for the geophysicist is to extend the time- lapse technique to stiff reservoir rocks such as carbonates. Most successful time-lapse cases have been obtained for clastic reservoirs (Landrø et al., 1999; Elde et al., 2000; Koster et al., 2000; Parr et al., 2003). Some of the major chalk fields have also shown good time-lapse results. However, time-lapse successful stories in stiffer rocks are limited (Calvert, 2005). The major reason for this is small changes in the seismic parameters compared to the background time-lapse noise level (Landrø 2006).

A method which is trying to overcome the stiff rocks seismic monitoring is the measuring of shift in critical offset caused by P-wave velocity changes within the reservoir layer (Landrø et al., 2004). In this study we will discuss the status and some future challenges that we see for the time-lapse refraction method.

Status

The principles of time-lapse refraction seismic are introduced by Landrø et al. (2004). The basic idea is shown in Figure 1. It exploits that the critical offset changes due to production changes. However, the major requirement for the method is the positive P-wave velocity change from the cap rock into the reservoir rock. The changes in PP-critical offset due to P-wave velocity changes in the reservoir can be approximated using (Landrø et al., 2004):

$$\frac{\Delta x_c}{x_c} = -\left(\frac{v_2}{v_{RMS}}\right)^2 \frac{\Delta v_2}{v_2}, \qquad (1)$$

where v2 and vRMS are the reservoir velocity and root mean square velocity of the overburden, respectively. It is assumed that the overburden velocity and thickness are constant. The critical offset, xc, is obtained from:

$$x_c = \frac{2z}{\sqrt{\left(\frac{v_2}{v_{RMS}}\right)^2 - 1}}, \qquad (2)$$

where *z* is the thickness of the overburden. As an example, for a reservoir at 2000 m depth with 2500 m/s and 1800 m/s P-wave velocity of reservoir and root mean square velocity of overburden, the PP-critical offset is 4150 m. Thus, a change in velocity of the reservoir of 1 % i.e. 25 m/s gives an 85 m change in critical offset. A sensitivity study (Fredy et al. 2007) shows a strong dependency of the critical offset variation to initial reservoir and overburden velocities estimation. This was expected, since critical offset change is directly related to velocity ratio of reservoir and overburden, as shown in Equation (1).

Many hydrocarbon fields are often associated with a significant S-wave velocity increase at the top reservoir. Therefore, the PS-critical offset can also be an alternative to PP-critical offset. However, the necessary input data is multi-component data, for instance seabed seismic data (Mehizadeh et al, 2005). The basic idea in this case is the same as for the PP case, as shown in Figure 2. In comparison with PP-critical offset, the PS-critical offset is shorter and the time-lapse detectability depends on the P- to S-wave velocity ratio. If this ratio remains constant by changing in the P-wave velocity of the reservoir, the time- lapse detecability will be lower for the PS compare to the PP case. However, the PS-critical offset equation is more complex than the PP-critical offset. For the example mentioned above, and with P- to S-velocity ratio of 2, the PS- critical offset is 2850 m. Furthermore, changing the P- velocity by 1 % and keeping the P- to S-velocity ratio constant, creates a 50 m reduction in the PS-critical offset. It is -1.8 % change in PS-critical offset which shows slightly lower time-lapse detectability compared to the PP-critical offset change of 2 %. Notice that the base PS-critical offset is almost half of the PP-critical offset. This is an advantage of the PS method compared to the PP method.

The reflection coefficient for both PP and PS at the critical offset has also interesting behavior. According to the Zoepprtiz equation the reflection coefficient at the critical angle (if fulfilled the criteria for time lapse refraction method) reaches a maximum which shifts clearly by changing the P-wave velocity in the reservoir. The PP- reflection coefficient (versus angle) for the example given above is shown Figure 3. Notice a clear shift at the maximum. This is also the case for PS reflection coefficient, as shown in Figure 4. However, for the post- critical angles, the head waves and the reflected waves will interfere and increase the amplitudes for post-critical offsets. Therefore, the maximum amplitude is shifted, and this shift is frequency dependent (Červený, 1961, 1962). In addition, there are some issues which should be addressed in this method:

- Thick and high velocity overburden layers,
- Top reservoir geometry,
- Refraction events from overburden,
- The lateral extension of the reservoir layer.

Presence of a high velocity layer in the overburden limits this method. However, a synthetic study (Landrø et al., 2004) showed that the overburden high velocity layer must be relatively thick to cause severe problems for the method.

Attenuation of overburden refraction events (considered as overburden noise) is a major issue for the time-lapse seismic refraction method. Despite the conventional (such as fk and tau-p) filters can effectively attenuate the overburden refraction, the refraction signal itself is also affected. A relatively recent study by Mehdizadeh et al. (2006) suggests source beam-steering acquisition for attenuation of water-column noise (in case of marine). There are some issues with this method. The major challenge is the effect of beam-steering on the final image, which is still under investigation. Another alternative for attenuation of the water-column noise is stacking the noises and then subtracting it from gathers (Landrø, 2007). There are some limitations for this method:

- Variation for the seabed should be negligible,
- The depth variation of the top reservoir interface should be comparable to the dominant seismic wavelength. In addition, the time-lapse repeatability is also an issue for this method, as it is for conventional time-lapse seismic.

Future challenges

The refraction time-lapse seismic will probably gain more interest in the future if the challenges associated with the method are met. However, only a proper field test can qualify or disqualify the effectiveness of the method. The future challenge with the method is mainly associated with how easy it is to detect clear changes in critical offset. The maximum amplitude offset is not at the same location of the critical offset due to interference of head waves. Despite the fact that it is often difficult to determine the exact critical offset position, time-lapse measurements of the shift at various offsets around the critical offset might still be used in a quantitative manner. Attenuation of overburden refraction which acts as noise to the critical offset data needs also more attention for complex overburden and seabed cases. Since the method is limited to simple top reservoir geometries at the time, the extension to the complex top reservoir shapes might be a challenge.

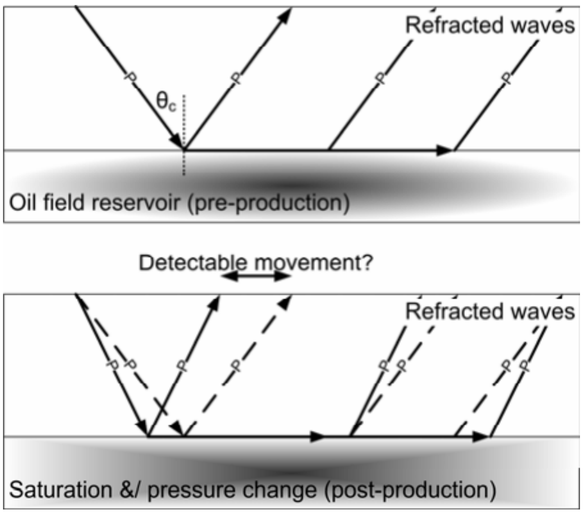

Figure 1: Basic principle of time-lapse PP-refraction seismic. A P-wave velocity change within the reservoir, caused by saturation and/or pressure change might create a significant shift in PP-critical offset at the surface.

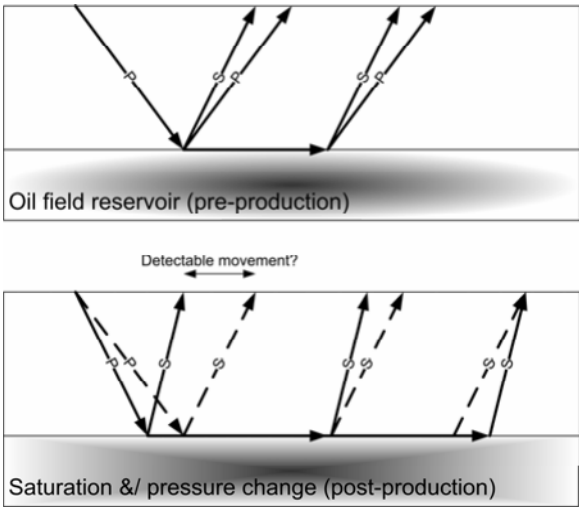

Figure 2: Basic principle of time-lapse PS-refraction seismic. A P-wave velocity change within the reservoir, caused by saturation and/or pressure change might create a significant shift in PS-critical offset at the surface.

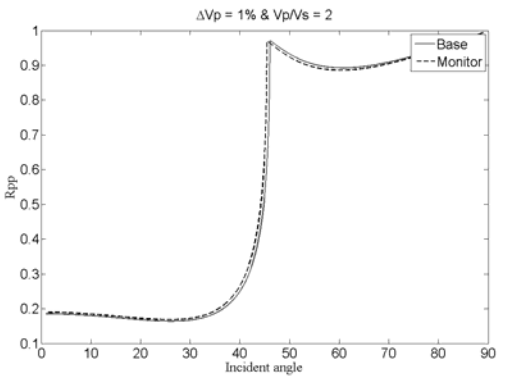

Figure 3: PP-reflection coeficient changes versus angle for 1 % increase in P-wave velocity.

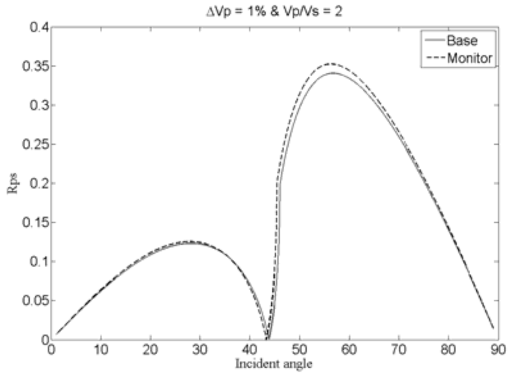

Figure 4: PS-reflection coefficient changes versus angle for 1 % P-wave velocity increase in monitor case.

Discussion and conclusions

The refraction time-lapse seismic might be a complementary or alternative method in the future, where conventional time-lapse seismic is limited. However, the method will only be proved by a real field data example. Although, the synthetic results are promising, there are important challenges that need to be met. The main challenge is how easy it is to detect clear changes in critical offset. Our understanding from relation between critical and maximum amplitude offset is immature. The focus on attenuation of overburden noise should be continued to effectively increase the signal to noise ratio around the critical offset. Applying this method on complex top reservoir shape is also a challenge. The time-lapse repeatability is another issue which is a same challenge for both refraction and conventional time-lapse seismic. Future work will include study of long-offset time-lapse seismic data.

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