Reservoir monitoring with True4D surface seismic data

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Summary

Harris et al., (2007) proposed a strategy, called True4D, for quasi-continuous reservoir monitoring with sparse data. True4D introduced two concepts for processing sparse but continuously recorded datasets: (1) dynamic imaging and inversion, (2) data evolution, and (3) model evolution. Arogunmati and Harris (2009, 2010) presented an approach to data evolution, i.e., inversion or imaging using data estimated from sparse recordings. In this paper, we examine the practicability of their approach, and present its application to full trace synthetic and field surface seismic data. The True4D approach is implemented by acquiring as little as 5% of the conventional 3-D survey data volume at small time intervals. Unrecorded data at each time interval are then estimated using recorded data at all intervals to produce an image with good spatial resolution of the subsurface. The high temporal resolution obtained using the True4D approach is its main benefit.

Introduction

The calendar-time temporal frequency of time-lapse surveys is a key factor in designing a quasi-continuous monitoring project; therefore the ability to vary the data acquisition frequency is of utmost importance. Attempts have been previously made to establish continuous and quasi-continuous seismic monitoring scenarios. These scenarios have been primarily designed around quick turn-around of acquired conventional 3-D survey sized seismic data volumes, .i.e., a short period of time from the time the data are acquired and the time the final image is delivered (e.g., Clarke et al., 2005; Lumley, 2001). With this strategy, shooting time, equipment availability, and manpower availability often puts a limit on how frequently the reservoir can be imaged (Houston et al., 2003).

Time-lapse monitoring using dedicated ocean bottom cables (OBCs) have gained traction in recent years, e.g. at the Valhall field (Barkved et al., 2005), Clair field (Foster et al., 2008), and the Chirag-Azeri fields (Foster et al., 2008). The ability to use fixed or buried receivers makes our True4D approach even more appealing by eliminating repeated receiver deployment costs and improving repeatability. Using synthetic and field data, we show the efficiency of True4D monitoring.

Method

Standard 3-D surveys over hydrocarbon reservoirs could take anywhere from a few weeks to a few months to complete (e.g., MacLeod et al.,1999). Depending on what kind of changes occur in the reservoir, a lot may vary in the time between the first shot and last shot recordings. Our approach is focused on reservoir monitoring projects where an early detection of abnormality in the reservoir is very important. Reservoirs with structural stability problems as well as sequestered CO_2 reservoirs fall within this category. Figure 1 shows a possible source deployment scenario for quasi-continuous imaging in a monitoring project over a period of three months. We have assumed the receivers are

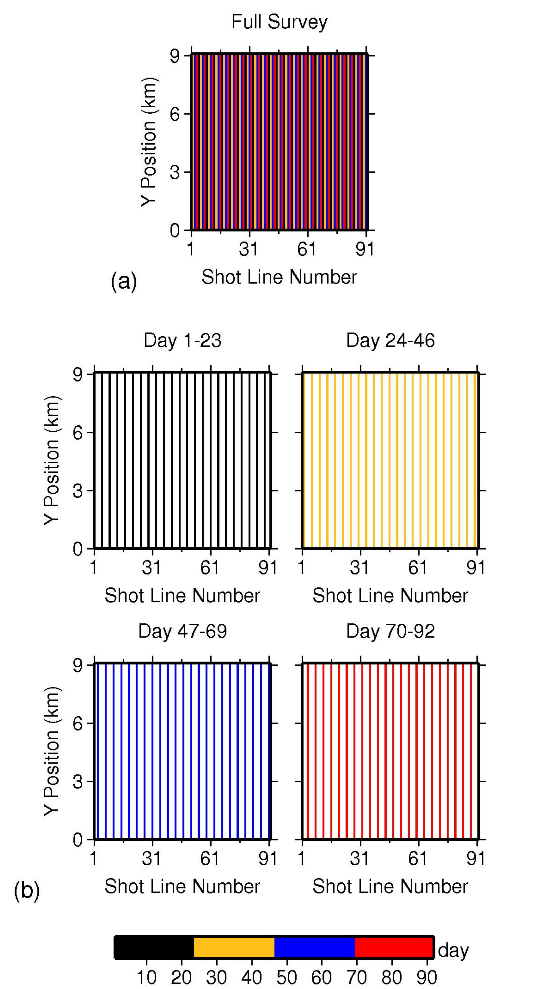

Figure 1: An idealized illustration of shot lines from a (a) standard complete survey, (b) split into four groups based on seismic shot time for true 4-D imaging.

dedicated OBCs and the airgun sources are towed by a source boat. With the conventional approach, one image will be produced from this survey (Figure 1a). However, if a temporal resolution of 3 weeks for the reservoir changes is desired, the deployed shots could be split into four groups as shown in Figure 1b.

Because each group is acquired within 3 weeks, the temporal resolution period of interest, four images of the reservoir over the course of three months can be produced. This concept/ideology can be extrapolated to any time frame. Presumably, a complete survey, such as that illustrated in Figure 1a, is deemed necessary to achieve the desired high spatial resolution. Splitting the complete survey into 4 sparse surveys (Figure 1b) will result in 4 images each with somewhat lower spatial resolution. Moreover, combining (e.g. stacking) these 4 sparse images will result in a similarly high-resolution image that would be obtained from the complete survey. If, however, the reservoir has experienced significant changes during this complete acquisition time, the image from the combined dataset may not have higher resolution than the sparse images.

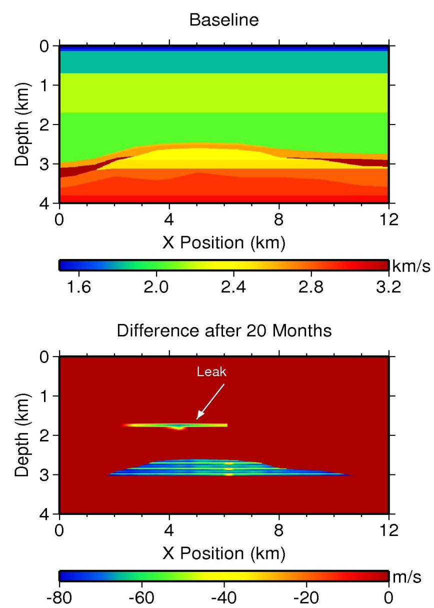

Figure 2: The 2D synthetic baseline velocity model, and the time-lapse velocity difference model after 20 months.

Synthetic Example

We use a synthetic reservoir model (2-D) to illustrate the practicability of the true 4-D approach. The reservoir is a modeled CO_2 storage site with simulated injection over a period of twenty months. An updated velocity model represents each month. We assume that a calendar-time temporal resolution of the reservoir changes of one month is appropriate for this process or project. The injected CO_2 is assumed to causes a maximum change of 3% velocity in the reservoir. The pre-injection synthetic velocity model, the 20th velocity and the difference model, are shown in Figure 2.

A leak was synthesized in the reservoir beginning in the 11th month. The addition of the leak was intended to test the ability of our approach to early detect the leak despite using sparse data, which is one of the main reasons for a quasi-continuous monitoring program at a CO_2 storage site. Dense synthetic data were computed for each model using an elastic wave equation algorithm. We assumed OBC cables and airgun shots. Spacing between shots and between receivers was based on conventional survey design. The synthetic data were then sub-sampled to 20% of the original size. With this sub-sampling scenario, a complete survey cycle is achieved after five months. Both regular and random sampling scenarios were tested. Sample receiver gathers are shown in Figure 3.

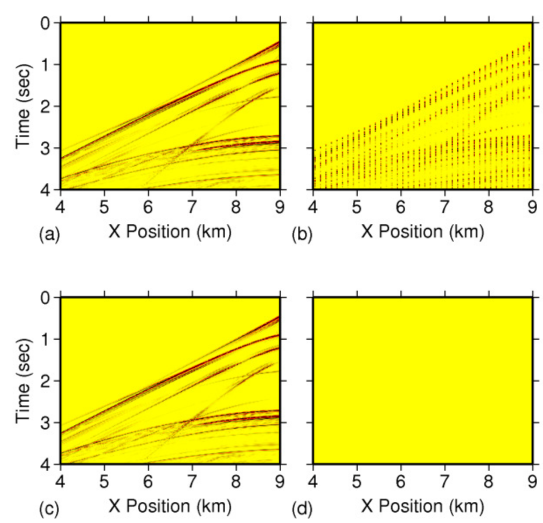

Figure 3: A comparison of the true, sparse, and estimated data for one receiver gather from the 12th-month data estimated in the 14th month. (a) The complete true data. (b) The 20% sparse data. (c) The estimated data. (d) The estimation error computed by taking the difference between the data in (a) and the data in (c).

After sub-sampling the synthetic datasets, we estimated discarded traces using the minimum weighted norm interpolation (Liu and Sacchi, 2001) then migrated the reconstructed gathers to produce seismic images.

As noted in Arogunmati and Harris (2009), the approach provides that data estimation be done each time new data are available until there is no further improvement on estimation error. Figure 4 shows seismic images obtained using complete data, and Figure 5 shows seismic images obtained using data estimated from 20% true data.

We refer to the time between the most recent survey used in data estimation and the survey of interest as the estimation slow-time lag (ESL). Therefore, if surveys 1-12 are used in estimating unrecorded data at survey 11, the ESL is one month. With our approach (Figure 5), the leak starts being delineated in the 12th month; one month after it actually occurred, and the image of the leak improves in clarity as more data becomes available and missing data are re-estimated.

Application to Field Data

After successfully testing the approach on synthetic data, we began testing it on the Valhall field time-lapse dataset. Our interest is the reservoir changes caused by injected water used in secondary recovery (Van Gestel et al., 2008). Injection started in early 2006, after the 6th seismic survey. The Valhall data have been used to observe time-lapse changes resulting as water migrates away from the injector well towards the producer well (Van Gestel et al., 2008). We subsampled the Valhall datasets from surveys 9 to 11 to 33% of their original sizes to simulate a True4D dataset and then applied the minimum weighted norm data-estimation-based approach. We then track the injected water using data from the 9th to 11th survey. Figure 6 shows migrated sections from the complete and estimated data for Survey 11 of the Valhall LoFS project. Figure 7 shows time-lapse difference sections from the complete and estimated datasets for Survey 11. For reference, the baseline survey was completed in November 2003 (Van Gestel et al., 2008), and the 11th survey was completed in November 2008. We clearly see the amplitude changes in the time-lapse images. The figures show that despite the large reduction in the size of individual survey datasets, the time-lapse "changes" were detected.

Conclusions

The quasi-continuous monitoring approach also known as True4D has been shown to be effective for reservoir monitoring where calendar-time temporal resolution of the reservoir changes is taken to be more important than spatial resolution. This paper examines the efficiency of the True4D approach using both synthetic and field data. We used synthetic shot time data to show how a conventional 3-D survey could be expanded into a True4D survey simply by scheduling the source line patterns appropriately. The synthetic seismic data examined were computed from 20 synthetic velocity models showing the state of a CO_2 sequestration reservoir over a period of 20 months at one month intervals. A leak in the reservoir was used to test the ability of the True4D approach to identify the leak features.

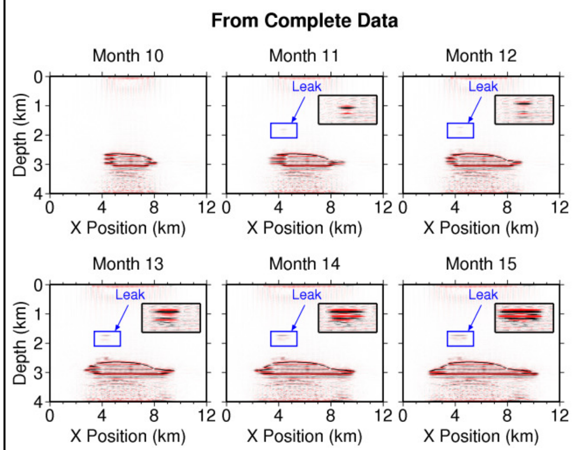

Figure 4: Time-lapse difference images obtained for month 11 using complete datasets in (a) month 10, (b) month 11, (c) month 12, (d) month 13, (e) month 14, and (f) month 15.

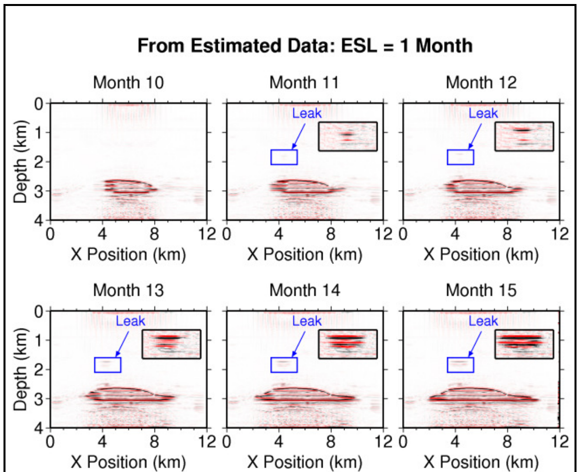

Figure 5: Time-lapse difference images obtained for month 11 using data estimated from accumulated sparse datasets in (a) month 10, (b) month 11, (c) month 12, (d) month 13, (e) month 14, and (f) month 15. For these images, the estimation slow-time lag (ESL) is one month.

We applied the True4D approach to the seismic time-lapse data from the Valhall field and the results are good. Future work will include dynamic estimation of unrecorded datasets.

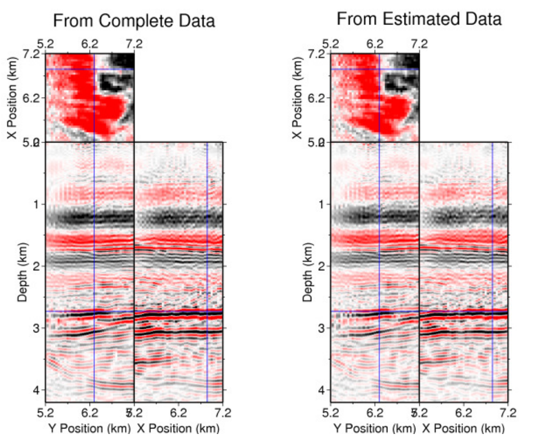

Figure 6: Migrated image from complete Survey 11 field data (left) and the migrated image from data estimated using 33% of the field data (right).

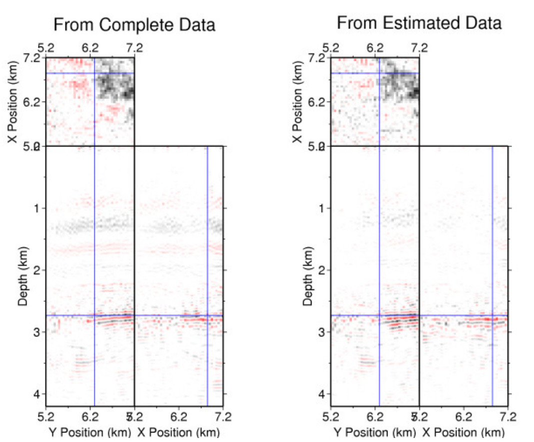

Figure 7: Time-lapse difference image obtained from the migrated image from complete Survey 11 field data (left) and the migrated image from data estimated using 33% of the field data (right).

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