Journal of Applied Geophysics 98 (2013) 144–159

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Field and synthetic experiments for virtual source crosswell tomography in vertical wells: Perth Basin, Western Australia

Majed Almalki [a,*], Brett Harris [a], J. Christian Dupuis [b]

[a] Curtin University, Department of Exploration Geophysics, Perth, Western Australia, Australia
[b] Université Laval, Department of Geology and Geological Engineering, Québec, Canada

ARTICLE INFO

Article history:
Received 16 January 2013
Accepted 31 August 2013
Available online 8 September 2013

Keywords:
Virtual source
Tomography
Vertical wells
Simultaneous WVSP

ABSTRACT

It is common for at least one monitoring well to be located proximally to a production well. This presents the possibility of applying crosswell technologies to resolve a range of earth properties between the wells. We present both field and synthetic examples of dual well walk-away vertical seismic profiling in vertical wells and show how the direct arrivals from a virtual source may be used to create velocity images between the wells. The synthetic experiments highlight the potential of virtual source crosswell tomography where large numbers of closely spaced receivers can be deployed in multiple wells. The field experiment is completed in two monitoring wells at an aquifer storage and recovery site near Perth, Western Australia. For this site, the crosswell velocity distribution recovered from inversion of travel times between in-hole virtual sources and receivers is highly consistent with what is expected from sonic logging and detailed zero-offset vertical seismic profiling. When compared to conventional walkaway vertical seismic profiling, the only additional effort required to complete dual-well walkaway vertical seismic profiling is the deployment of seismic sensors in the second well. The significant advantage of virtual source crosswell tomography is realised where strong near surface heterogeneity results in large travel time statics.

1. Introduction

A cost-effective and low-impact method for recovering velocity information between vertical wells is likely to be of considerable interest for the groundwater, geothermal, geotechnical and conventional/unconventional hydrocarbon industries. For any site where large volumes of fluids are injected into or pumped from the subsurface, crosswell tomography may provide a useful constraint on the distribution of the mechanical and hydraulic properties. Here, the term ‘tomography’ refers to a technique that uses direct travel times between in-hole sources to receivers to reconstruct the velocity distribution between two wells.

Developing a hydrostratigraphic model between wells is often based on interpolation between wire-line logs. However such interpolation can and should be enhanced by cross well methods where they can be applied at reasonable cost. In subsurface storage for fluids, such as what occurs during aquifer storage and recovery (ASR), it is often important to track the fate of the injectant. ASR operations are often intended to inject water when it is abundant and to retrieve water when it is in short supply or high demand. For arid to semi-arid climates such as that of Perth, Western Australia, aquifer management may mean banking (i.e., injection) in the winter and the retrieval of stored water in hot summer periods. The water chemistry and clogging potential in different sediment layers depend on geochemical interactions between the injected water and formation sediments (Descourvières et al., 2010) and on the discharge rate from the well (Lowry and Anderson, 2006). It is our intent to test the potential of a method of recovering crosswell velocity distribution that may assist in constraining the geometry of subsurface models required for hydraulic or reactive transport modelling.

A number of techniques can be used to recover a crosswell velocity distribution without using downhole sources. Blakeslee and Chen (1996) investigated a method that can be used to simulate crosswell tomography using seismic sources on the surface. The travel times are measured at receivers deployed in both wells and compared to the travel time calculated on the basis of an assumed inter-well velocity model. This method is akin to crosswell tomographic inversion based on vertical seismic profiling (VSP), which modifies an initial velocity model based on the travel time measurement between receivers in closely spaced wells. Zhou (2006) used the first arrivals from VSP, in which receivers are deployed in a single vertical borehole and a number of seismic sources are distributed on the surface to construct a three-dimensional (3D) velocity-depth model for a salt dome structure using a tomographic approach described as deformable-layer tomography (DTL). This method is suitable for areas where geological and geophysical information is known for model parameterisation. That is, the velocity information for some regions on the 3D model must be supplied for the inversion process to stabilise the solution. However,

* Corresponding author. Tel.: +61 421002658.
E-mail addresses: m.almalki3@postgrad.curtin.edu.au (M. Almalki), b.harris@curtin.edu.au (B. Harris), christian.dupuis@ggl.ulaval.ca (J.C. Dupuis).

0926-9851/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jappgeo.2013.08.021

the limitation of these methods is the requirement of an accurate travel time and a priori knowledge of velocity structure. We address this particular problem by using a method based on seismic interferometry (Wapenaar et al., 2010).

The advantage of direct-wave seismic interferometry using a controlled/active source is an important application for this research. Seismic interferometry creates pseudo-seismic recorders by cross-correlating wavefields received at two different positions without known model parameters (Wapenaar et al., 2006, 2010). As a historical side note, the idea of seismic interferometry was originally put forward by Claerbout (1968), who stated that the autocorrelation of a wavefield from a source buried in horizontally layered media is a response from an impulsive source on the surface. Using source–receiver reciprocity, Bakulin and Calvert (2006) developed an approach to redatum surface sources into deviated borehole by cross-correlating the wavefield recorded in two receiver positions. This technique is called the 'virtual source method' (VSM). For imaging proposes, Bakulin and Calvert (2006) suggest that a preferable application of a virtual source experiment is in deviated or curved 3D trajectory wells. The algorithm of the VSM can be written as

$$D_{\alpha\beta}(t) = \sum_{k=1}^{N} S_{k\alpha}(-t) * S_{k\beta}(t), \tag{1}$$

where

$D_{\alpha\beta}(t)$ is equivalent to the response at a selected downhole virtual source (α), measured by any downhole receiver (β),
$S_{k\beta}(t)$ is the response recorded by the receiver (β),from the *kth* source at the surface,
$S_{k\alpha}(-t)$ is the time-reversed portion of the response recorded by (α) from the *kth* source at the surface, and
N is the source element, and '*'denotes temporal convolution.

The application of time-reversed acoustics can be implemented for tomographic inversion to construct the velocity information between two receivers. Zhou and Schuster (2000) provided an alternative approach called the Phase-Closure principle, which integrates the concept of seismic interferometry directly into the tomographic inversion process. For their work both sources and receivers are inside the boreholes. Torii et al. (2006) conducted a small-scale laboratory based VSM experiment. While the authors retrieved the direct wave, they did not proceed in the analysis of the tomographic inversion. Also their experiment was not intended to represent or analyse the complexities and heterogeneity that exist in the full scale field experiments we present.

Vasconcelos and Snieder (2008) presented a new approach for processing based on seismic interferometry of passive data using multi-dimensional deconvolution (MDD). In essence, the computation of this method required a receiver's array coverage in which all receivers simultaneously contributed to matrix inversion regularisation. The application of MDD was then modified by Minato et al. (2011), who could stabilise the MDD solution using a singular-value decomposition (SVD) approach. This method is intended to better retrieve down-going and up-going wavefield amplitudes compared to the crosscorrelation VSM (Bakulin and Calvert, 2006).

Minato et al. (2013) used the SVD approach for borehole configurations to evaluate the quality of the wavefield retrieved by MDD interferometry. Their experiment examined the effect of data redundancy due to the surface source distribution. In localised surface source positions (i.e., sources are only in one side of the boreholes), the MDD method retrieved the first arrival amplitude, and the result further improved when including near-surface scatterers. While many published works discuss the possibility of virtual source tomography, none analyse the field application of the method or how well tomographic inversion can recover velocity distribution.

In this paper we explore methods for recovering the velocity distribution between two vertical wells that do not require actual in-hole seismic sources to be deployed. Our approach combines the recovery of accurate crosswell travel times with the VSM (Bakulin and Calvert, 2006) and tomographic inversion. We refer to our approach as 'virtual source crosswell tomography' (VSCT). We require only a line of surface sources and the first arriving wavelet as recorded at in-hole receivers in two vertical wells. We do not require or create full virtual source records for our VSCT approach.

Synthetic modelling of seismic records is used to assess the field parameters and processing requirements for the application of VSCT. The method we develop is then applied to dual-well walkaway vertical seismic profiling (WVSP) field data acquired in two monitoring wells at the Mirrabooka Aquifer Storage and Recovery (ASR) trial site in Perth, Western Australia. In addition to testing VSCT for vertical wells, a site-specific objective is to better characterise aquifers above and within the ASR trial injection zone by investigating the P-wave velocity's structure between two wells.

2. Method

2.1. Generating the virtual source

The virtual source method can be used to simulate a set of sources below complex overburden to achieve improved subsurface images. For vertical wells, this method requires simultaneous acquisition using surface sources and receivers located in two wells, as shown in Fig. 1. To generate a virtual source at R_α, we crosscorrelate the wavefield from each surface source recorded by the receiver R_α in the first borehole with the wavefield recorded by the receiver R_β. Next, the crosscorrelated traces are summed over the surface sources. This idea is the general principle of the VSM presented in Eq. (1) (Bakulin and Calvert, 2006). Note that, for our virtual source crosswell tomography we isolated the first arrival information from the dual-well WVSP by applying time muting to remove other wavefields. Wavefield separation in crosscorrelation seismic interferometry is commonly used for improving the reflection response (Mehta et al., 2007; van der Neut and Bakulin, 2008).

The surface source distribution is an important factor in creating a virtual source (Minato et al., 2013). For a given receiver pair, one can get a kinematically correct wavefield if (i) surface sources are in the stationary phase region only, or (ii) surface sources of equal strength

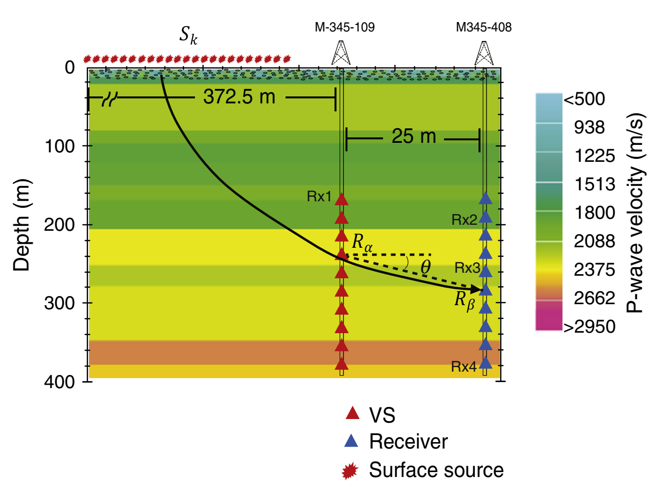

Fig. 1. Acquisition geometry for virtual source cross well tomography in vertical wells. The receiver R_α in well-109 is converted to a virtual source. The angle theta is the take-off angle of the ray defined between the horizontal plane and a line connecting the virtual source position at R_α and the receiver R_β.