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Large well-spacing crosswell seismic imaging for deep gas reservoir mapping and description

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Summary

We present here a successful case study using the crosswell seismic method to image complex reservoir structure and derive a petrophysical model of a deep gas reservoir. The availability, resolution, and overall quality of crosswell seismic information can significantly impact reservoir management and production optimization, as well as the accuracy of reserves assessment. Crosswell seismic imaging is the technology that fills the information gap between surface seismic and well logs. With crosswell seismic, critical reservoir characteristics are directly imaged, not statistically estimated. Faults and stratigraphic features can be clearly identified prior to drilling. Fluid movements and saturation changes can be monitored in time-lapse mode.

In order to properly characterize and map the lateral variation and extent of a newly discovered deep gas reservoir, Daqing Oilfield organized this pilot project to extend their direct experience with crosswell seismic technology in their own reservoir environments. The crosswell seismic imaging from this survey has been very valuable, and the results of the project include: (1) the imaging results show the complex reservoir structure in high-resolution, including several small faults between the survey wells; (2) high-resolution images of the geology between the wells were produced; (3) the crosswell seismic reflection images were correlated to reservoir tops, which will be used for reservoir thickness evaluation, and reservoir development between the wells; (4) a reservoir structure map and a petrophysical model were generated using the crosswell information; and (5) a high-resolution velocity image and structure between the wells were produced through AVA inversion.

Through this project, Daqing Oilfield has demonstrated the application of crosswell seismic technology in their reservoirs. The success of this challenging project, acquiring crosswell seismic data over 832 m well spacing, has demonstrated the feasibility of using crosswell seismic technology in Daqing's gas field, which has well spacings between 800 m to 1,200 m.

Introduction

Standard reservoir mapping methods are limited by a lack of data falling between surface and well-bore measurements. While 3-D seismic interrogates large subsurface volumes, it does not provide sufficient resolution for determining reservoir characterization or for monitoring fluids within the reservoir. Well logs and cores do deliver high resolution and precise quantification, but they provide limited information, given that they sample only a small portion of a very large heterogeneous volume. In addition, data accuracy can be reduced by distortion from rocks and fluids encountered during acquisition.

One of the reasons for the growth of the use of crosswell seismic has been the availability of reliable acquisition equipment, which can obtain data over realistic oilfield well separations in hostile operating conditions. A practical technique for generating high-resolution images, crosswell seismic draws heavily from proven geophysical imaging technology used in seismic operations. The crosswell seismic concept is simple: perform the seismic survey from inside the reservoir instead of from the surface. Standard wireline technology is used to deploy a seismic transmitter or source into one well and a receiver array, or arrays, into one or more adjacent wells. High-bandwidth data are then collected between the wells, directly across the reservoir or other zone of interest. By imaging from the reservoir, many practical advantages result: (1) vertical resolution of 2 to 5 feet (1 ~ 2 meters) up to 10 to 100 times better than surface seismic's; (2) measurements directly referenced in depth and co-located with well log data, removing the uncertainties of time-depth conversions; (3) highly repeatable measurements providing unparalleled precision for time-lapse monitoring; and (4) bypassing of near-surface and overburden effects.

During last a few years, Daqing Oilfield has discovered new deep gas fields around the outside boundary of their existing oilfields. But these newly discovered gas fields are much deeper than the existing oilfields, and their reservoir structure is extremely complicated with many faults and volcanic craters disrupting the reservoir formation. The major gas reservoir zones have been broken up by local volcanic eruptions and tectonic activities. It is impossible to map the reservoir structure and its lateral extent with existing low resolution surface seismic data.

Crosswell seismic technology has been identified by Daqing as a high resolution reservoir description and characterization tool. The project objectives are to (1) map the lateral changes and extent of reservoir formation between wells; (2) provide critical reservoir distribution information for optimizing the gas filed development plan, and (3) select in-fill well locations between the existing exploration and evaluation wells with large well spacing. The high-resolution imaging capabilities of crosswell seismic make it a suitable tool for production enhancement and optimization in mature reservoirs.

Acquisition summary

One crosswell seismic profile data was collected from the Daqing Oilfield during September 2005. The source well for this profile was the SS.2.17 well and the receiver well was the SSG.2 well, and the well spacing between the two wells at the surface was 832 m. The objective imaging zone was from 2,500 m to 3,400 m. During the data acquisition, the downhole seismic source coverage was from 2,154 m to 3,093 m, and the downhole receiver coverage was from 2,229 m to 3,366 m. Both the source and receiver spacing were 3 meters. The source sweep frequency range was from 100 Hz to 1,000 Hz. Since the well spacing was very large compared with normal crosswell seismic profiles in China, we used a specially configured source to increase the downhole seismic source energy by 6 dB and improve signal-to-noise ratio.

Operational issues were encountered due to high noise levels in the wells. The major noise source was from the gas movement between different zones behind the casing. With the experience now gained, in the future a different approach to well preparation may be useful. In this way, crosswell seismic can be applied routinely and efficiently to image the complex deep gas reservoirs in Daqing Oilfield in high-resolution.

Crosswell seismic data over 832 m well spacing was successfully acquired and the acquisition equipment operated robustly, reliably and efficiently for extended periods in actual field conditions. The data was used to image the reservoirs between the wells at higher resolution than is possible with other technologies.

Data processing and analysis

The objectives for the crosswell seismic profile SSG.2 ~ SS.2.17 were to: (1) provide reservoir tops, thickness and reservoir development; and (2) transform the reflection image to log data phase (AVA inversion). In addition, due to the tall section both reflection data from above and below the source and receiver positions (upcoming and downgoing reflections) were used to cover the entire interval of interest. The processing procedure for profile SSG.2 ~ SS.2.17 for reflection imaging was chosen in light of the objectives, unknowns and assumptions. The same processing flow was used for both upcoming and downgoing reflection images. First the data were converted from the EGG field SEG-Y format to the internal Z-Seis SEG-Y format. Each trace was noise edited with diversity stacking and cross-correlated with its pilot sweep. The correlated data were then stacked to generate a 3m depth increment in both the source and receiver well. Because of tube-wave noise, both coherent and random in the data, a 17-point median filter was applied to reject the upcoming and downgoing tube waves. In addition the data were zero-phase band-pass filtered with an Ormsby filter (225Hz ~ 250Hz ~ 750Hz ~ 850Hz) prior to picking.

P-wave first arrivals were then identified and picked in four different domains: Common Receiver Gather (CRG), Common Source Gather (CSG). Common Offset (Receiver depth – source depth) Gather (COG), and Common Mid-depth ((Receiver depth + source depth)/2) Gather (CMG). The picked first arrivals were input into a 3-D anisotropic traveltime inversion. The 3-D anisotropic traveltime tomography algorithm operates in a rectangular coordinate system with the vertical axis being TVD (true vertical depth). Velocity image values are positioned in the rectangular depth coordinate system. The velocity image is derived using the P-wave first arrival times and receiver and source locations as the input to the traveltime inversion (Bube and Langan, 1999).

The starting model is then ray traced and traveltimes are calculated. The calculated traveltimes are compared with the measured traveltimes and the starting model is updated through non-linear continuation steps to minimize the traveltime residuals. As each continuation step is updated the inversion constraints are decreased resulting in higher resolution as the iterations progress. The final tomographic inversion is displayed in Figure 1.

For reflection imaging of the reservoir interval the objective was to use the upcoming and downgoing *P*-wave reflections. All arrivals in the wavefield that contribute coherent noise to the final stacked image are removed through spatial filtering. Prior to transforming the time domain data into a data volume in depth, the time domain data are filtered to remove coherent modes (which do not stack out of the final image) other than upcoming reflection energy and downgoing reflection energy. The unwanted modes are attenuated using spatial filters, usually *f-k* fan filters or variations on median filters, applied in CRG, CSG, and COG gathers. The wavefield-separated data were deconvolved with a zero-phase spiking filter. The deconvolution operator was calculated for a window from 25 ms before and 100 ms after the direct arrival time with 1% white light. The filter length was 32 ms.

The reflection amplitudes recorded in crosswell data are affected by several factors that are not related to the reflection coefficient of a reflecting horizon. The goal of amplitude normalization is to correct the amplitudes of the time domain data before mapping. The amplitude normalization used was a true balance computed trace-by-trace over the time window –10 to +100 ms either side of the first arrival time.

The wavefield-separated data were VSP-CDP depth mapped, as in offset VSP data processing. The velocity model from the traveltime inversion is used in tracing reflection raypaths. The VSP-CDP mapped data set is a 3-D data cube with mid-depth and offset (distance between the two wells) as the two domains. The post-map prestack depth migration was carried out on the VSP-CDP mapped data cube to collapse all the diffractions and produce the final reflection image (Washbourne and Bube, 1998).

Since there are a wide range of incidence angles present in a crosswell data set and the wavelet and reflection character change with incidence angle, another natural domain for data analysis is the angle-transformed AVA data cube. Angle selection was used to select angles that maintain adequate SNR while best approximating the vertical incidence (0^o) response. Reflection events should be flat in AVA gathers. Small velocity errors may result in small dips for events in AVA gathers. Due to the lack of wellbore deviation information, the velocity model was less than optimal. This caused the flat reflection events to persist for shorter angle ranges. Thus, the data were angle transformed and stacked over a short, reflection incidence angle range.

A depth domain Ormsby band-pass filter of 8-12-80-100 cycles/km was applied together with a long window trace balance. The final combined composite upcoming and downgoing reflection image is displayed in Figure 2, which is overlaid on the final tomographic image. In comparison with the 30 Hz surface seismic data, the crosswell seismic profile has more than 10 times higher resolution than the former, and contains tremendous details including sub-seismic structural features. The interpreters are currently using this final reflection image to map the detailed reservoir structure between the two wells.

Another objective of this seismic crosswell survey was to derive petrophysical properties form the data. This process applies inversion methods based on linearized approximations to Zoeppritz equations to forward model crosswell seismic traces. The incidence angles present in crosswell seismic data, due to borehole geometry, usually cover a wide range of reflection angles from 40 to 80 degrees from the vertical as opposed to the more vertical paths typical in surface seismic data. Amplitude vs. reflection angle (AVA) response to various formation properties is increasingly used in estimation of petrophysical properties from seismic. The changes in V_p, V_s, and density with angle due to the properties of the formation make AVA response sensitive to many petrophysical properties. This inversion uses the reflectivity as a function of angle to recover V_p, V_s, and density using a constrained, nonlinear inversion algorithm.

The AVA gathers are input to the AVA inversion algorithm and produces dV_p/V_p, dV_s/V_s, and $d\rho/\rho$. In effect these are the instantaneous compressional velocity changes, the instantaneous shear velocity changes, and the instantaneous density changes along the seismic trace. The low frequency trend is then added back to the inversion output in order to generate the final AVA V_p, V_s, and density inversions. In addition to these results the V_p and density results were combined in order to generate an acoustic impedance section. The final impedance results are displayed in Figure 3, and the final density results are displayed in Figure 4. These AVA inversion results can be used to derive the petrophysical properties of the reservoir formation through interpretation.

Conclusions

Through this project, PetroChina and Daqing Oilfield have successfully demonstrated the operation and application of crosswell seismic technology in Daqing Oilfield. The success of this project has been attributed to the careful planning and good cooperation before and during the operation. The management commitment to the project has been an essential factor in addressing all the initial challenges of introducing a new technology to the area. With the experience now gained, the operations and the technology can be optimized for local conditions.

The crosswell seismic data has been used to image the reservoir structure between the large spacing wells in higher resolution than is possible with other technologies. In conclusion, the crosswell seismic survey has been very valuable to Daqing: (1) The operation of crosswell seismic data acquisition has been demonstrated in Daqing's deep gas field with complex geology; (2) The field operations in Daqing were conducted safely, and the field equipment operated reliably during the project; (3) The imaging results show the complex reservoir structure in high-resolution, including several small faults between the survey wells; and (4) AVA inversion has produced a high-resolution velocity image and structure along the profile between the wells, and they can be used to derive the petrophysical properties of the reservoir formation through interpretation. Overall, the crosswell seismic reflection imaging has been most successful at imaging the complex structure and this is recommended as a primary imaging method in this area.

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Large well spacing crosswell seismic profile mapping deep gas reservoir

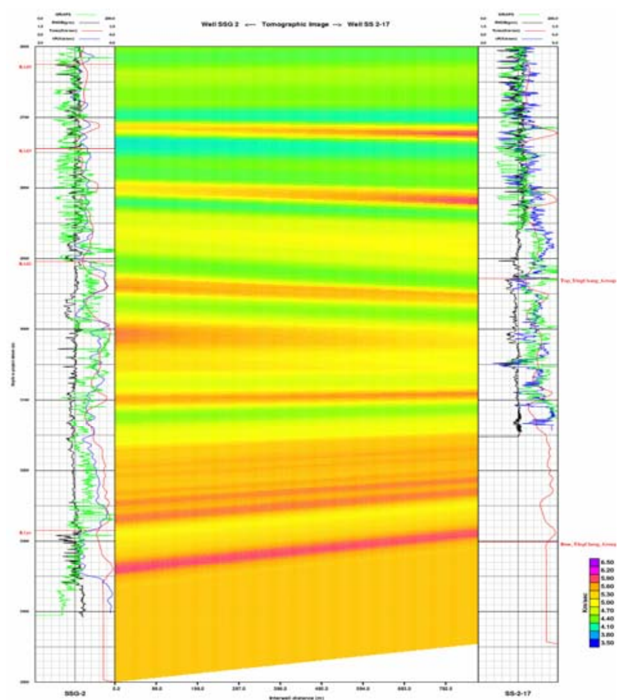

Figure 1: Final tomographic inverted velocity model.

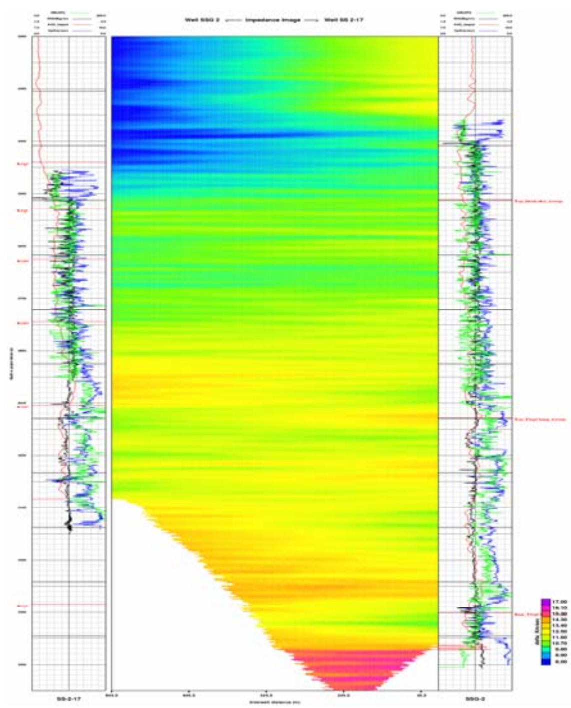

Figure 3: Final AVA-Vp inverted acoustic impedance image.

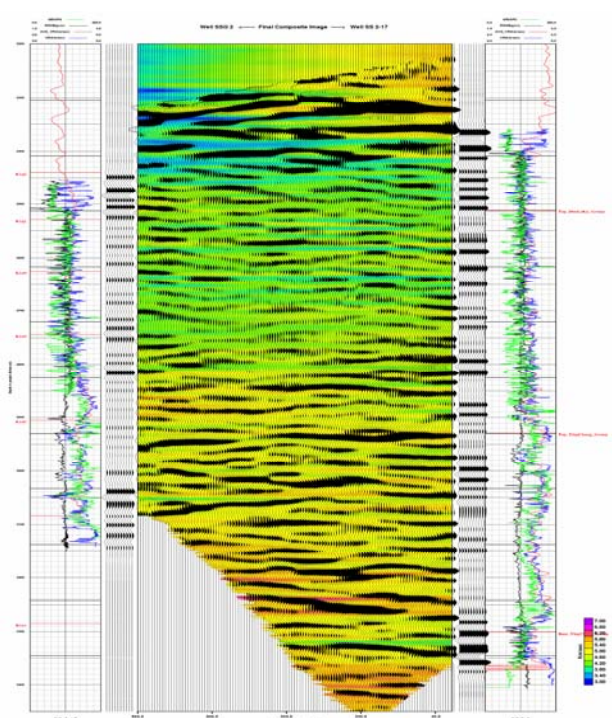

Figure 2: Final composite combined reflection and tomographic inversion image.

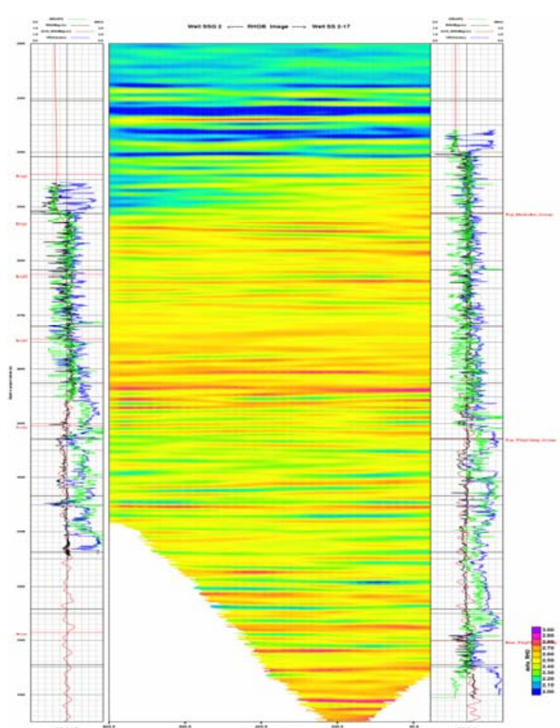

Figure 4: Final AVA inverted density image.

EDITED REFERENCES

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