2011 CSPG CSEG CWLS Convention

Evidence of Shallow Gas in the Queen Charlotte Basin from Waveform Tomography of Seismic Reflection Data

Eric M. Takam Takougang*
Simon Fraser University
eta9@sfu.ca
and
Andrew J. Calvert
Simon Fraser University

Summary

Eight Seismic reflection lines were collected in 1988 across the Queen Charlotte sedimentary Basin of western Canada by the GSC (Geological Survey of Canada). Acoustic waveform tomography was used to form high-resolution quantitative images of the P wave velocity and attenuation factors, following a specific data preconditioning and inversion strategy. The field data were inverted between 7 and 12 Hz with attenuation introduced for frequencies greater than 10.5 Hz. Results from line 88-05 show a V-shape low velocity anomalous zone which corresponds to the location of a chain of pockmark structures, where antigenic carbonate chimneys occur. Parallel, subvertical bands of anomalously low velocity are interpreted as pipe-like chimneys resulting from gas ascension.

Introduction

The Queen Charlotte sedimentary Basin (QCB) is the largest Tertiary basin on the west coast of Canada with an area of approximately 80,000 km^2 (500 km long and 150-200 km wide). This large basin is bounded to the south and to the north by Vancouver Island and Alaska respectively, and is terminated to the east by the Coast Plutonic Complex and to the west by the Queen Charlotte fault, which separates the North American plate from the Pacific plate (Woodsworth, 1991). The geological structures of the basin, its history as well as its hydrocarbon potential have been thoroughly documented (e.g., Rohr and Dietrich, 1992; Woodsworth, 1991).

The purpose of this work is to further the study of the upper part of the basin by quantitatively imaging its structure using 2-D waveform tomography applied to the limited offset seismic reflection data. Velocities and anelastic attenuation models were derived from the inversion of 4 lines across Hecate Strait: 88-07, 88-06, 88-05 and 88-04. Synthetic tests have demonstrated the ability of waveform tomography to image within and below shallow gas (e.g., Brossier et al., 2009; Ghazali et al., 2010). In this paper, we interpret some features in the derived velocity models derived as arising from shallow gas in the Queen Charlotte Basin.

Waveform tomography

We used the 2-D visco-acoustic waveform tomography approach in the frequency domain, as described in (Pratt, 1999). A detailed description of this waveform tomography approach can be found in the above paper. In essence, the objective of the inversion is to generate an update to a starting velocity and when used, to an attenuation model, by minimizing iteratively the misfit between the forward modeled data and the field data, using the negative gradient. The gradient is computed by multiplying the forward modeled wavefield by the backward propagated data residual.

The Queen Charlotte data are characterized by a limited maximum offset of 3770 m and a relatively high starting frequency of 7 Hz, which makes the inversion procedure highly non-linear. Therefore, we designed a strategy to ensure a successful convergence of the inversion to a likely global minimum. This strategy comprised a specific data preconditioning and inversion strategy described in detail in Takougang and Calvert (2011). In essence, the preconditioning of the data consists of the removal of coherent noise using f-k filtering, and, amplitude balancing and scaling for 2-D wave propagation. The inversion strategy consisted of successively recovering shallow to deep structures in the subsurface velocity and attenuation models (a layer stripping approach). The shallow structures were recovered using near offset and early arrivals and the deeper structures were recovered by additionally including far offsets and late arrivals.

The inversion was performed between 7 and 12 Hz and attenuation was introduced above 10.5 Hz. The starting velocity model was derived from travel-time tomography and the starting attenuation model was a homogenous Q_p model with $Q_p = 100$. This inversion strategy was successfully applied in Takougang and Calvert (2011) to image a section of line 88-06. However, we observed an increase in the non-linearity of the inversion on line 88-05 due to the presence of shadow zones in the input data (Figure 1). In these areas, the inversion has difficulty in recovering the correct phase of the data. For this reason, we refined our inversion strategy by alternating between phase-only and amplitude-plus-phase inversion for the early frequencies, i.e. frequencies ranging between 7 Hz and 8.5 Hz. The phase-only inversion was performed with $\tau = 0.8$ s and the amplitude-plus-phase inversion with $\tau = 1.6$ s. τ is a time damping term.

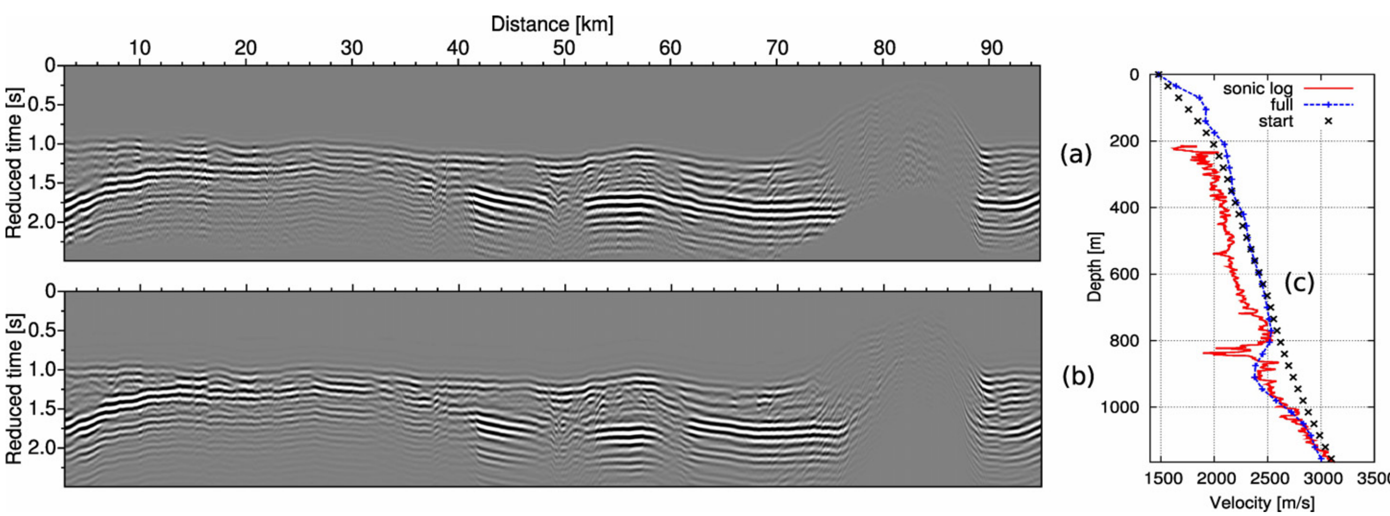

Figure 1: (a) field data low pass filtered to 12 Hz and (b) predicted data displayed in a common offset gather (offset = 2915 m). A high degree of similarity exits between both data, especially in the sediment i.e. between 0-70 km. Note the present of shadow zones between 40-60 km in (a), that were successfully recovered in (b). (c) shows the sonic log from the Sockeye B-10 well superimposed with the starting model (black) and the waveform tomography model (bleu) at x = 18.3 km.

Results and Discussion

Velocity, attenuation and perturbation velocity models derived from the inversion are displayed in Figure 2. The maximum depth of penetration is limited to 1.2 km due to the limited source-receiver offset (3770 m) of the input data. Generally the results show 2 main geological features: the upper Miocene-Pliocene sedimentary section and mostly Triassic basement rocks. The sedimentary rocks are characterized by velocities ranging between approximately 1700-3500 ms^{-1} and by attenuation values ranging between Q_p^{-1} = 0-0.03. Between 70-90 km, basement rocks are represented in the model by velocities of 4000-5500 ms^{-1} and an apparent attenuation as high as Q_p^{-1} = 0.05-0.07 (Q_p = 15-20). These high attenuation values suggest that scattering and elastic effects, which are not included in the inversion, may not be negligible in this part of the model, especially at the basement/sediment interface. Sediment layering is disrupted between x = 47-51 km by a V-shape low velocity anomalous zone with a velocity of ~ 1700-1800 ms^{-1} (Figure 2), below which, Miocene/Pliocene faulting are presents (Figure 2). The location of this anomalous zone between x = 49-50 km corresponds to a chain of seafloor pockmarks, where antigenic carbonate chimneys occur (Barrie et al., 2010); there is also a shadow zone at this location in the input data (Figure 1). Pockmarks and carbonate chimneys in the QCB have been interpreted to be related to hydrocarbon seepage (Halliday et al., 2008; Barrie et al., 2010). The origin of carbonate is considered to be derived by microbial oxidation of the hydrocarbon fluid (Hovland et al., 2005). The hydrocarbon fluid in the area might have migrated upward through local fault planes. Underneath the pockmark structures, high attenuation of Q_p^{-1} = 0.05-0.06 may be associated with faulting (Figure 2). Between x = 38-40 km and deeper at x = 66 km, parallel, oblique bands with anomalously low velocity and high attenuation values of Q_p^{-1}=0.06 at x= 66 km and Q_p^{-1}= 0.045-0.05 between x = 38-40 km (Figure 2), are interpreted as pipe-like chimneys resulting from gas ascension. The chimney located between x = 38-40 km might be responsible for the presence of the shadow zone in the input data between 40-48 km (Figure 1).

Overall, a good match exits between the predicted data and the field data. The match is considerably better over the thick sedimentary section, i.e. between x = 0-70 km and x = 90-95 km, than where shallow igneous basement is present, i.e. between x = 70-90 km (Figure 1). Waves propagating into basement are strongly attenuated, both by heterogeneity and P-S conversion, which is not included in the inversion. Therefore, it is not surprising that the match between the field and synthetic data is less accurate in that area. A generally good match also exists between the sonic log and the 1-D profile from the 12 Hz model (Figure 1 (c)). However, velocities from the 1-D profile are faster than the sonic velocities between 200-750 m depth. It should be noted that the sonic log does not exactly tie to the line and the location of the well was projected to the nearest points on the line for the extraction of the 1D profile. The mismatch may be related to a difference in geological structure at the well location and the projection of the well location onto the seismic line.

Conclusions

The application of waveform tomography to seismic reflection data from the Queen Charlotte Basin has enabled the identification of pockmark structures and pipe-like gas chimney in the recovered velocity and attenuation models. Overall, the field data and the predicted data match very well and the sonic log also matches a 1-D velocity function extracted from the derived 2-D velocity model. This result shows that with specific preconditioning of the data and a good inversion strategy waveform tomography of relatively short offset reflection data can be used to image shallow geological features.

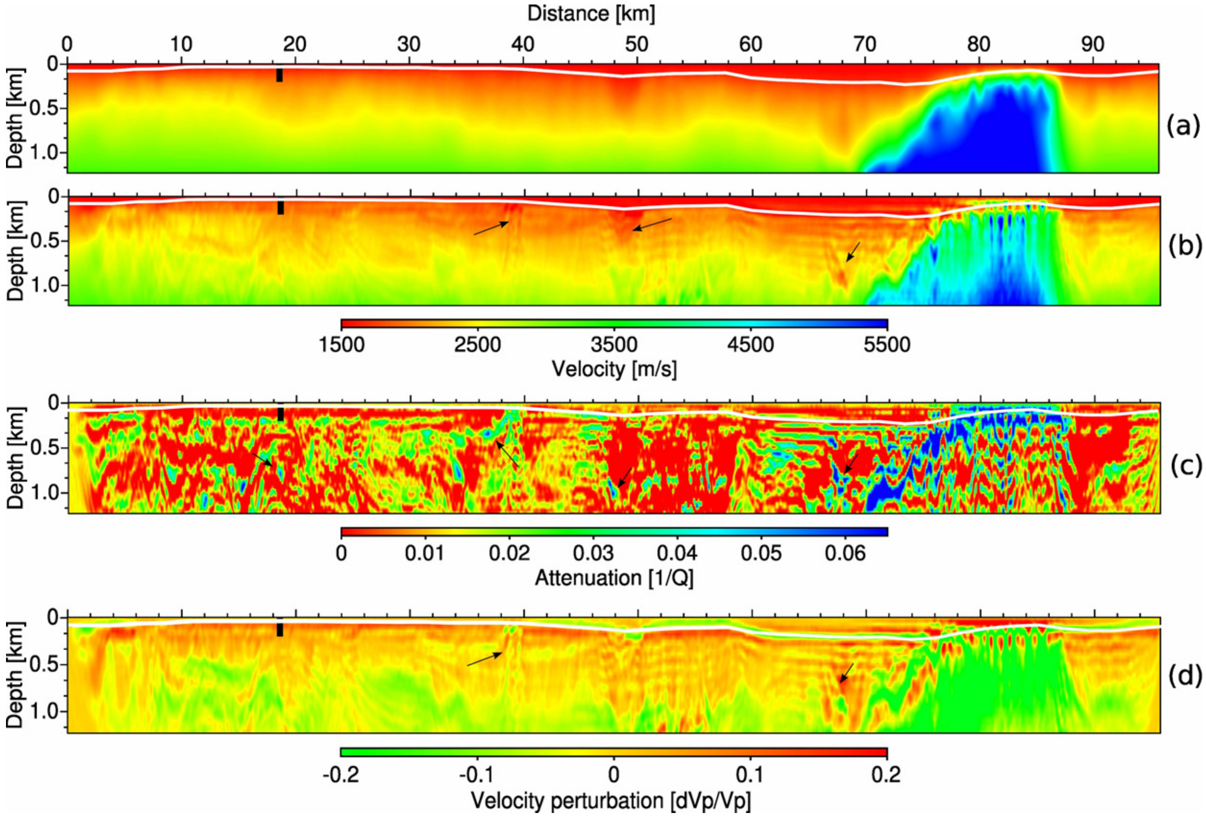

Figure 2: (a) Starting model from travel-time tomography. (b) Waveform tomography velocity model at 12 Hz, (c) attenuation model and (d) fractional velocity perturbation. The black tick segment indicates the location of the Sockeye B-10 well and the white line the sea floor. The arrow at x = 50 km indicates the location of pockmark structures and the arrows at x = 39 km an 66 km indicate pipe-like gas chimneys.

Acknowledgements

We are grateful to Gerhard Pratt, who provided us with his waveform tomography code. The sonic log from the Sockeye B-10 well was provided by Divestco. This project was funded by the Natural Sciences and Engineering Research Council of Canada.

References

Barrie, J. V., S. Cook, and K. W. Conway, 2010, Cold seeps and benthic habitat on the pacific margin of canada: Continental Shelf Research, in press, corrected proof.

Brossier, R., S. Operto, and J. Virieux, 2009, Two-dimensional seismic imaging of the valhall model from synthetic obc data by frequency domain elastic full-waveform inversion: SEG Technical Program Expanded Abstracts, **28**, 2293–2297.

Ghazali, A.R., 2010, Multi-dimensional non-linear full waveform inversion of gas clod reflection data using genetic algorithm and a blended acquisition approach: SEG Expanded Abstracts **29**, 935-939.

Halliday, E., J. Barrie, N. Chapman, and K. Rohr, 2008, Structurally controlled hydrocarbon seeps on a glaciated continental margin, Hecate Strait, offshore British Columbia: Marine Geology, **252**, 193–206.

Hovland, M., H. Svensen, C. F. Forsberg, H. Johansen, C. Fichler, J. H. Foss, R. Jonsson, and H. Ruesltten, 2005, Complex pockmarks with carbonate-ridges off mid-norway:Products of sediment degassing: Marine Geology, **218**, 191 – 206.

Pratt, R. G., 1999, Seismic waveform inversion in the frequency domain, part 1: Theory and verification in a physical scale model: Geophysics, **64**, 888–901.

Rohr, M. M. K., and R. J. Dietrich, 1992, Strike-slip tectonics and development of the Tertiary Queen Charlotte Basin, offshore Western Canada: evidence from seismic reflection: Basin Research, **4**, 1–19.

Takam Takougang, E., and A. Calvert, 2011, Application of waveform tomography to marine seismic reflection data from the Queen Charlotte Basin of western Canada: Geophysics, in press, corrected proof.

Woodsworth, G., 1991, Evolution of hydrocarbon potential of the queen charlotte basin, British Columbia: Geological Survey of Canada, **Paper 90–10**, 569 pp.