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Identification of duplex waves from vertical basement faults, Fox Creek region, Alberta: Implications for a basement rooted regional flower structure

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Summary

This study investigates the use of duplex waves – waves that have reflected from both a subhorizontal and a subvertical boundary – to image basement faulting. Imaging of sub-vertical boundaries has been quite challenging in the past due in part to the fact that waves reflected from subvertical boundaries do not reach the surface. Methods such as Vertical Seismic Profiling (VSP) has been used in the past; however, the information received from the borehole vicinity can be limited and in the case of the crystalline basement in the current study area, no borehole information is available. In this study, we demonstrate key concepts with the use of finite-difference modelling and 2D seismic raw shot gather from a deep crustal seismic profile acquired as part of the LITHOPROBE PRAISE program. Events with the expected moveout for duplex wave geometries were observed in a LITHOPROBE seismic profile. These observed phases are consistent with reflections arising from sub-vertical faulting as well as the Winagami Reflection Sequence (WRS) a set of sill intrusions seen within the upper and middle crust of the Alberta crystalline basement. Mapping of these basement features can provide insights into the nature of fault system within the Kaybob Duvernay region.

Introduction

Basement reactivation is of critical importance for understanding the role of basement structure in controlling geologic complexes such as the presence of optimally oriented faults and fractures. During the last decade, exploitation of unconventional resources has been a major focus of oil and gas development with studies indicating a vast amount of induced seismicity attributed to hydraulic fracturing (Atkinson et al., 2016). While most fluids are injected into the sedimentary layers, earthquakes with magnitudes ≥ 2.5 have occurred within the crystalline basement. Basement structures have been seen to influence the overlying sedimentary layers especially in places prone to induced seismicity (Bao and Eaton, 2016; Shah and Keller, 2017; Skoumal et al., 2018). Although some basement related faults in this region have been identified using seismic attributes (Chopra et al., 2017; Eaton et al., 1999; Green and Mountjoy, 2005), faults that may control the location of induced earthquakes are often challenging to detect using seismic reflection images alone in Alberta (Bao and Eaton, 2016). A major problem seen in mapping of faults through conventional seismic reflection interpretation is the uncertainty due to complexity of the subsurface geology. Problematic cases such as this can be seen in the Precambrian crystalline basement of Alberta (Ekpo and Eaton,2018). Faults with geometries such as sub horizontal thrust faults or vertical strike-slip faults, hosted within the crystalline basement, which lack clear marker reflections are difficult to image by conventional seismic data alone due to various factors such as the obscuring effect of multiples (Eaton, 1995).

The current study area is in a seismogenic region of Alberta (near Fox Creek) where sub vertical basement rooted faults have been interpreted (Figure 1(a)). Strike slip faults are difficult to map in conventional seismic because they tend to be vertical (Chopra and Marfurt, 2007; Wang et al., 2016). Figure 1(b) shows an example of the study area on a 2D seismic section. Here, we infer that the faults extend into the basement but are not easily discernible due to the obscuring effect of multiples. Figure1(c) is a flower structure model for the region which has been invoked in this area (Eyre et al., 2019). These faults are interpreted to form a deep-rooted N-S oriented basement fault but is not very well imaged using conventional seismic methods.

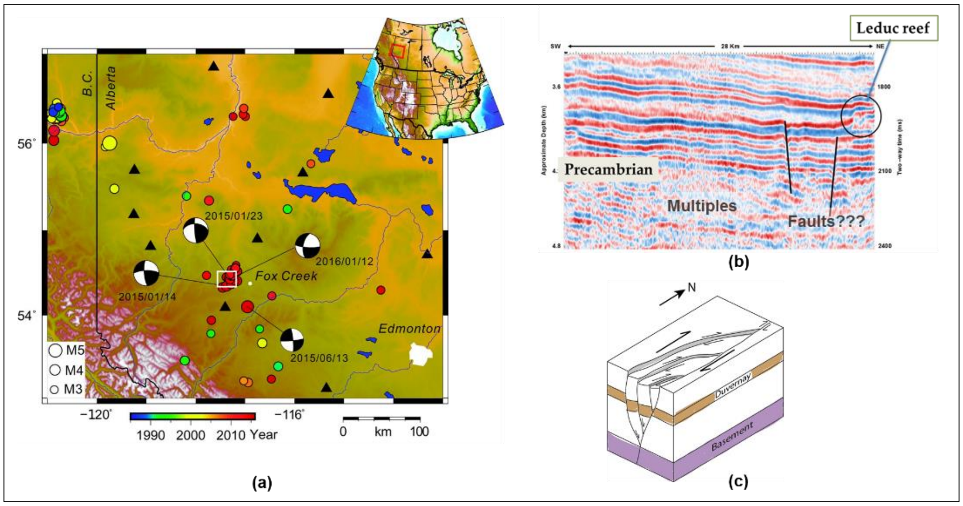

Figure 1 (a) Seismicity near Fox Creek region and their focal mechanisms. The beach ball denotes strike slip faults (Bao and Eaton, 2016) (b) LITHOPROBE seismic profile showing sedimentary layers (vertical exaggeration 8:1) from the Kaybob-Duvernay region, where induced seismicity has occurred. Several basement faults are evident, as indicated by the black lines (c) Flower structure as depicted by Eyre et al. (2019). Our study is based on a deep rooted fault structure within the Alberta crystalline basement and extends upward to the sedimentary layers within the Kaybob-Duvernay region.

In this study, we introduce the concept of duplex waves for interpreting basement faults. Duplex waves (Figure 2b) are reflections that bounce twice, initially from a sub-horizontal boundary and then from a sub-vertical boundary (or, the kinematic equivalent reflection in the opposite order) (Khromova and Link, 2010). These waves may be recorded in areas where both reflective vertical features and a suitable deep reflector exist (Marmalyevskyy et al., 2005).

Theory and Method

During seismic acquisition, all types of wave modes are recorded e.g. primary reflected wave, direct, multiple, refracted, shear etc. However, during the conventional data processing stage, the primary reflected energy is enhanced while the other wave modes are deemed as noise and subsequently suppressed.

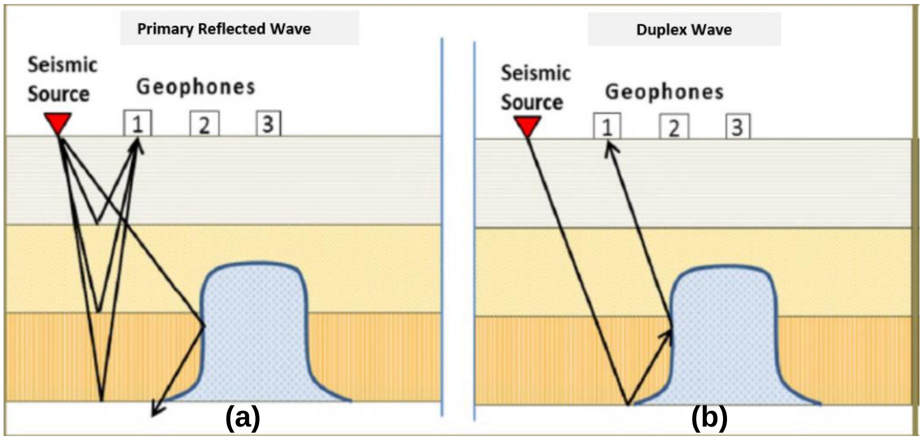

Figure 2 Comparisons between a primary reflected ray path (a) and Duplex wave raypath (b). Modified from Introduction to Duplex Wave Migration TetraSeis, Client guide 2013.

One type of wave mode is the duplex waves, routinely found in seismic data sets that contain sub-vertical subsurface features (Marmalyevskyy et al., 2005). Duplex wave energy undergoes two bounces of primary reflectors during its wavefront travel path before it returns to the surface (Figure 2b). This secondary bounce energy appears as a form of coherent noise when observed on a raw seismic record. Results from modelling duplex waves show that they differ in their kinematics from primary reflected waves, thus procedures such as normal moveout (NMO), dip moveout (DMO), and prestack time migration attenuate the signature of duplex waves. Due to their double reflection, these waves can reach the surface.

Finite Difference Modelling

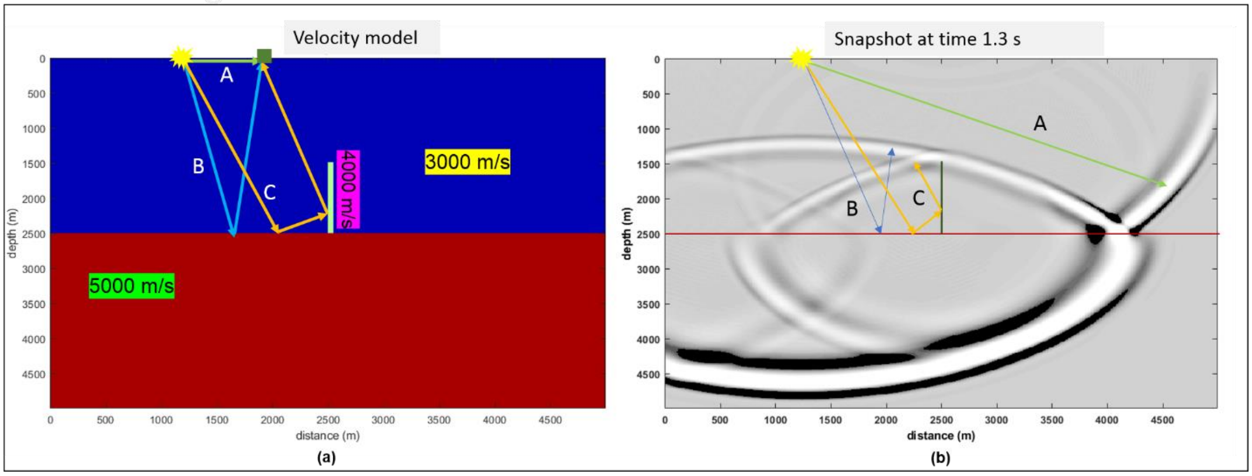

Figure 3 (a) A two layered velocity model with a vertical thin boundary (b) A snapshot at 1.3s created from the velocity model in (a) using a Ricker wavelet with a dominant frequency of 10Hz. A denotes direct wave raypath; B denotes reflected wave raypath; C denotes duplex wave raypath. The duplex wave appears as a form of coherent noise.

Figure 3a shows a 2D velocity model. A Ricker wavelet with a dominant frequency of 10Hz is used. For the 2^{nd} order 2D acoustic finite difference method (Youzwishen and Margrave,1999), the spacing interval is 10m. The actual grid used is 500 by 500 with a time interval of 0.004sec and 2999 time steps are calculated.

Real Datasets

As a component of Canada's LITHOPROBE program (Clowes et al., 1996), 627 km of deep crustal seismic-reflection profiles were acquired in 1994 for the Peace River Arch Industry Seismic Experiment (Eaton and Ross, 1999; Ross and Eaton, 2002). A segment of a raw shot gathers from the LITHOPROBE PRAISE L20b is analyzed in Figure 4. The seismic profile is close to the induced earthquakes occurrence. Two duplex wave geometries are observed.

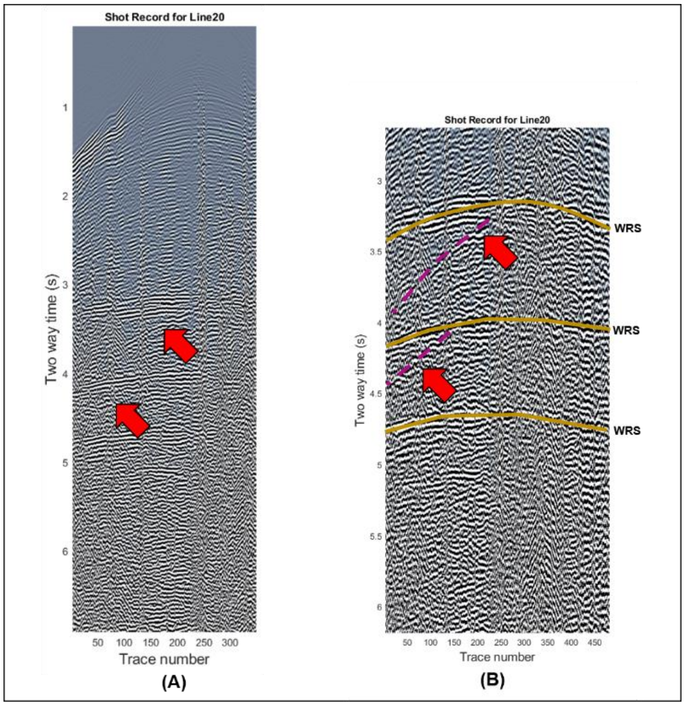

Figure 4 (a) Segment of a raw shot record for 2D seismic profile 20b (b) Interpreted duplex waves (highlighted with pink dash lines) identified on the raw shot gather of Line 20b. WRS: Winagami Reflection Sequence.

Conclusions

Recognition of pre-existing faults is important for induced seismicity risk assessment. Strike slip faults are prominent in the Alberta crystalline basement. With sparse data only from old drill cores, potential field data and deep seismic reflection, we aim to explore a different method in locating these sub vertical faults. Duplex waves can be recorded in the proximity of a vertical structure. However, during conventional processing, the duplex wave is seen as noise and suppressed. Finite acoustic modelling in this study, shows that duplex waves are readily identifiable within geological features steeper than 60°. In order to enhance the stability of the process, a deep horizontal reflection boundary should be specified. This reflection boundary is chosen based on its pervasive continuity through the survey and proximity to the sub vertical feature under consideration. The Winagami Reflection Sequence (WRS) has a high impedance contrast within the crystalline basement can be correlated over distances of tens of kilometers. These features are well suited to our study and provide a base in understanding the fault architecture of the basement. The raw shot gathers of the LITHOPROBE seismic profiles were analysed and duplex wave energy was observed. This observation helps to improve consideration for our flower structure model which involves a deep rooted subvertical fault extending up into the Duvernay Formation. This study gives more insight into the fault system and tectonic evolution within the Alberta crystalline basement and improves imaging of sub vertical features. Being able to identify the duplex wave provides the first direct evidence for vertical basement faults and gives more details about reactivating basement rooted faults.

Acknowledgements

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References

Atkinson, G.M., Eaton, D.W., Ghofrani, H., Walker, D., Cheadle, B., Schultz, R., Shcherbakov, R., Tiampo, K., Gu, J., Harrington, R.M. & Liu, Y. (2016). “Hydraulic fracturing and seismicity in the western Canada sedimentary basin”. In: Seismological Research Letters 87.3, pp. 631–647.

Bao, X. & Eaton, D.W. (2016). “Fault activation by hydraulic fracturing in western Canada”. In: Science 354.6318, pp. 1406–1409.

Chopra, Satinder & Kurt Marfurt (2007). “Curvature attribute applications to 3D surface seismic data”. In: The Leading Edge 26.4, pp. 404–414.

Eaton, David W. (1995). “Lithoprobe basin-scale seismic profiling in central Alberta: influence of basement on the sedimentary cover”. In: Bulletin of Canadian Petroleum Geology 43.1, pp. 65–77. ISSN: 00074802.

Ekpo, E., Eaton, D. W., & Weir, R. (2018). Basement tectonics and fault reactivation in Alberta, Canada. *IntechOpen*.

Eyre, T. S., Eaton, D. W., Zecevic, M., D’Amico, D., & Kolos, D. (2019). Microseismicity reveals fault activation before M w 4.1 hydraulic-fracturing induced earthquake. *Geophysical Journal International*, *218*(1), 534-546.

Green, D. G., & Mountjoy, E. W. (2005). Fault and conduit controlled burial dolomitization of the Devonian west-central Alberta Deep Basin. *Bulletin of Canadian Petroleum Geology*, *53*(2), 101-129.

Khromova, I. U. and B. H. Link (2010). “Using duplex wave migration for mapping of fracture zones in oilfields from Northern Russia”. In: 72nd European Association of Geoscientists and Engineers Conference and Exhibition 2010: A New Spring for Geoscience. Incorporating SPE EUROPEC 2010. ISBN: 9781617386671.

Marmalevskyi, N., B. H. Link, Y. Roganov, A.Kostyukevych, and Z. Gornyak (2007). “Duplex wave migration - A practical and effective tool for imag ing vertical boundaries”. In: 69th European Association of Geoscientists and Engineers Conference and Exhibition 2007: Securing the Future. Incorporating SPE EUROPEC 2007. ISBN: 9781605601557.

Shah, A. K., & Keller, G. R. (2017). Geologic influence on induced seismicity: Constraints from potential field data in Oklahoma. *Geophysical Research Letters*, *44*(1), 152-161.

Skoumal, R. J., Brudzinski, M. R., & Currie, B. S. (2018). Proximity of Precambrian basement affects the likelihood of induced seismicity in the Appalachian, Illinois, and Williston Basins, central and eastern United States. *Geosphere*, *14*(3), 1365-1379.

Youzwishen, C. F., & Margrave, G. F. (1999). Finite difference modeling of acoustic waves in Matlab. *the 11th Annual Research Report of the CREWES Project*.