Investigation of turning rays in the Western Canada Sedimentary Basin

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ABSTRACT

Multi-offset vertical seismic profiles (VSPs) were recorded in the Western Canada Sedimentary Basin (WCSB) at Pike's Peak, Saskatchewan and Cygnet, Alberta, with receivers located from surface to depth in the borehole. For offset shots the minimum traveltime of direct arrivals to receivers in the borehole occurs at increasing depth for increasing shot offset. We attribute this phenomenon to turning rays caused by vertical velocity gradients. Identification of turning rays is important for additional constraint on the near surface velocity model.

First-arrival traveltimes were used to estimate velocity anisotropy in the presence of vertical velocity gradients. At Pike's Peak a numerical model consisting of two layers with vertical velocity gradients of 3.1 s^{-1} and 1.2 s^{-1} respectively, and global anisotropy parameters of ε = 0.12 +/- 0.02 and δ = 0.30 -/+ 0.06, yielded first-arrival traveltimes that matched the observed traveltimes well. At Cygnet the first-arrival traveltimes were fit well by a five-layer isotropic velocity model that contained strong vertical velocity gradients in the near surface. Linear velocity gradients of 10 s^{-1} and 5 s^{-1} were applied to layers one and two, respectively. In both cases shallow receivers were crucial for constraining the vertical velocity field. At Pike's Peak, constraint on the near surface velocity field in turn constrained the parameters of anisotropy at depth.

Introduction

Newrick, Lawton and Spratt (2000, 2001) used first-arrival traveltimes from multi-offset VSPs in the WCSB to estimate the Thomsen (1986) parameters of anisotropy, ε and δ. They showed that it is important to accurately estimate the vertical velocity profile, and the near surface velocity field, to constrain the parameters of anisotropy at depth. An accurate near surface velocity field is also required for depth migration if we are to focus images at depth. Turning rays are useful both for assessing vertical velocity gradients and for tomographic inversion of the near surface velocity field. We are specifically interested in creating a vertical velocity profile, that contains vertical velocity gradients and velocity anisotropy, to match computed and observed VSP first-arrival traveltimes.

Uhrig and Van Melle (1955) used traveltimes measured at a single receiver in a borehole to estimate their "anisotropy factor *A*" which they define as the ratio of bedding-parallel velocity to bedding-perpendicular velocity. We designed similar experiments with full coverage of receivers in the borehole, and used forward modelling to match computed first-arrival traveltimes to those observed.

Pike's Peak

Pike's Peak heavy oil field is located 40 km east of Lloydminster, Saskatchewan (Figure 1). The field produces from the 15 - 25 m thick sands of the Lower Cretaceous Waseca Formation (van Hulten, 1984) at a depth of approximately 500 m. The overlying strata consist of Cretaceous shales and interbedded sands and shales. The Pike's Peak field is situated over a very gentle anticline caused in part by salt dissolution of deeper Devonian evaporites (van Hulten, 1984; Orr et al., 1977). Over the limited extent of the survey we have assumed horizontal layering.

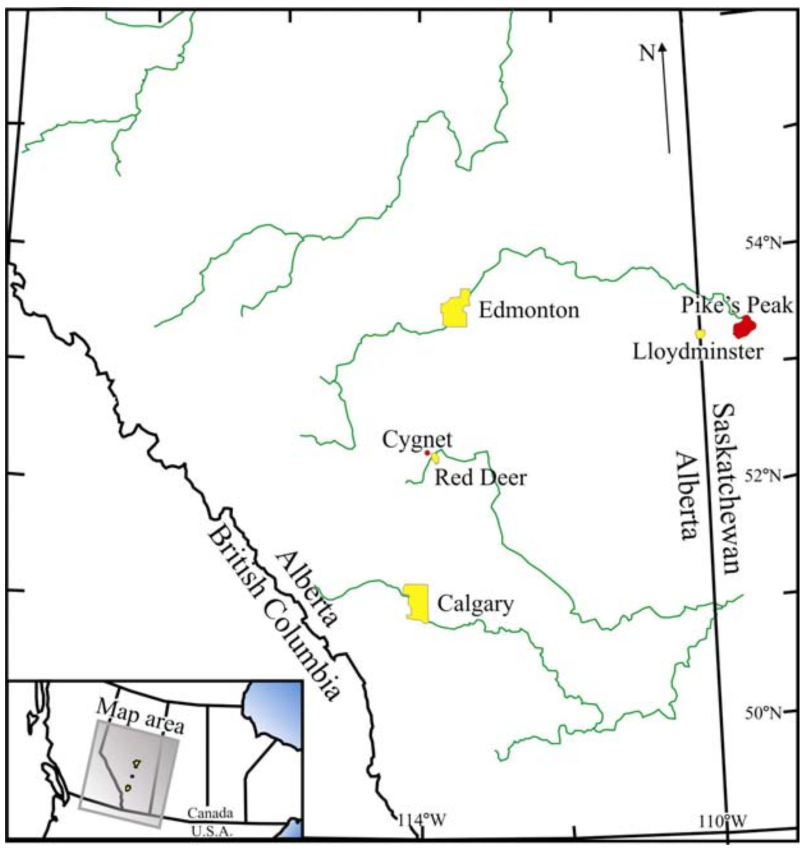

Fig. 1: Location map for the Pike's Peak and Cygnet VSP surveys.

The vertical borehole, 15-6-50-23W3, has a terminal depth of 580 m. A multi-offset VSP was recorded (Figure 2) with source points from –23 m to 450 m along an azimuth of 207° from the well. Receivers were located in the borehole between depths of 27 m and 515 m below surface, at 7.5 m intervals. A three-component five-level tool with receivers at 15 m spacing was used to record the VSP. The vertical component for shot gathers at offsets –23 m and 450 m are shown in Figure 3.

Layered model

We initially created a model with discrete layers. Even with substantial ray bending, the isotropic model was unable to yield traveltimes that matched those observed in the field. A global anisotropic solution was then investigated in which ε and δ were assigned to be constant within all the layers of the model.

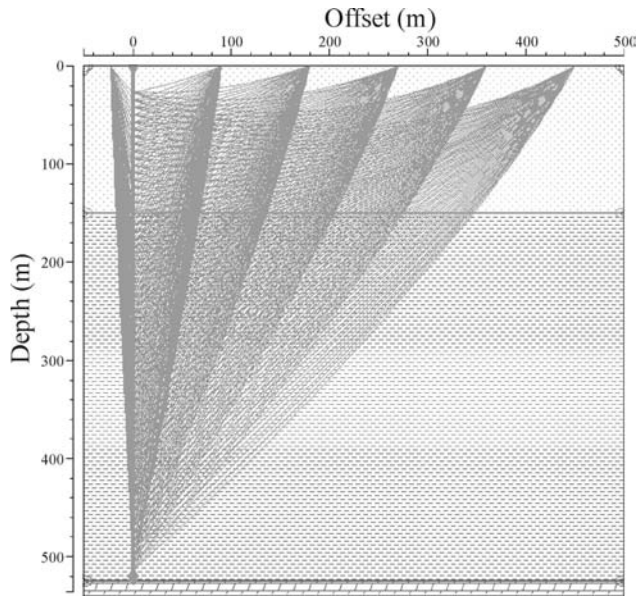

Fig. 2: VSP layout at Pike's Peak.

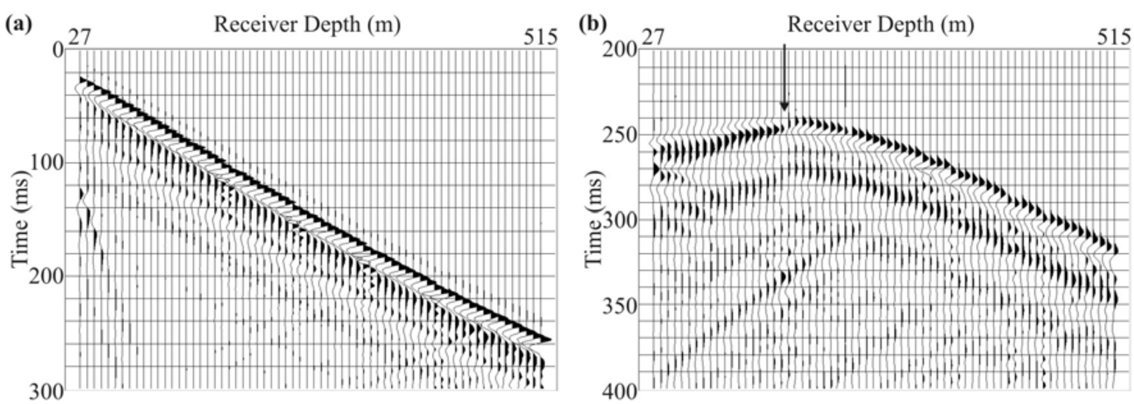

Fig. 3: Pike's Peak shot gathers for offsets (a) -23 m and (b) 450 m. The arrow indicates the "slowness cross-over depth" which is the depth the apparent vertical slowness changes sign.

Iteration over values of ε and δ produced an optimum solution for arrivals at deep receivers of ε = 0.1 and δ = 0.3. Reasonable solutions for deep receivers were also obtained with ε = 0.2 and δ = 0.2, and ε = 0.3, δ = 0.15, but the match at shallow receivers was poor for all values of ε and δ.

Turning rays

The Pike's Peak common shot gathers have a minimum traveltime that occurs with increasing depth in the borehole with increasing offset. Figure 3b clearly shows a negative apparent vertical slowness at shallow depths. We interpret this phenomenon to indicate turning rays due to a vertical velocity gradient. Slotnik (1959) discussed the offset dependence of traveltimes in a linear velocity gradient media. The minimum traveltime to a receiver in the well is recorded at the depth of maximum penetration (Slotnik, 1959) for this ray. We term this depth to be the "slowness crossover depth" because it is the depth at which the vertical apparent slowness changes sign. For receivers located shallower than this depth in the borehole, the energy has already passed through the maximum depth of penetration and will be turning upwards when it is recorded by the receiver array. For receivers located below the crossover depth, the energy is still down going as it intersects the borehole.
The interpretation of the crossover depth is supported by the polarity of the first-arrivals on the vertical component geophone in the well. Above the crossover depth, polarities on the vertical receiver are reversed (Figure 3b) compared with those below the crossover depth. The angle of rotation from the vertical to the direct component is the incident angle of first-arrival energy at the borehole. We observe also that at the slowness crossover depth, the P-wave energy is polarised orthogonal to the borehole (i.e. the ray is normal to the borehole).

Gradient model

A gradient model was investigated for both isotropic and anisotropic cases. To calculate traveltimes in models with isotropic and anisotropic layers with vertical velocity gradients, we used a commercial numerical modelling package (GXTechnologies GX2). A single-layer solution could not be found to satisfactorily match modelled and observed first-arrival traveltimes, and consequently a two-layered model was developed, based on the zero-offset VSP. The gradient in the top layer (0 - 150 m) was 3.1 s^{-1} whereas that in the deeper part of the well was 1.2 s^{-1}. To avoid a velocity discontinuity between the two layers, the maximum vertical velocity in layer 1 was set to be equal to the minimum vertical velocity in layer 2. Global values of ε and δ were assigned to each layer.

An isotropic model was investigated first, but computed first-arrival traveltimes for offset shots were found to be unable to adequately match the field first-arrival traveltimes over the full receiver aperture, for all gradients tested (e.g. Figure 4a). Although the shapes of the computed traveltime depth curves are similar to the field traveltime curves, the values of the traveltimes could not be matched using only an isotropic model with a vertical velocity gradient.

The final model tested comprised of two layers that incorporated both vertical velocity gradients and velocity anisotropy. Velocity gradients were constrained by the zero-offset traveltimes, and we systematically iterated over all combinations of ε = 0, 0.05, 0.10, 0.125, 0.15, 0.20, 0.25 and 0.30 and δ = 0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40 during raytracing. Figure 4b shows observed and calculated first-arrival traveltimes for values of ε = 0.10 and δ = 0.30. The residuals between the modelled and observed first-arrival traveltimes were evaluated using a least squares approach, and these are contoured in Figure 5 over the range of ε and δ tested. The error in picking the field data was estimated to be +/- 2 ms (i.e. one sample interval). Thus, from the residuals plotted in Figure 5, we conclude that an optimum solution is given by ε = 0.12 +/- 0.02 and δ = 0.30 +/- 0.06.

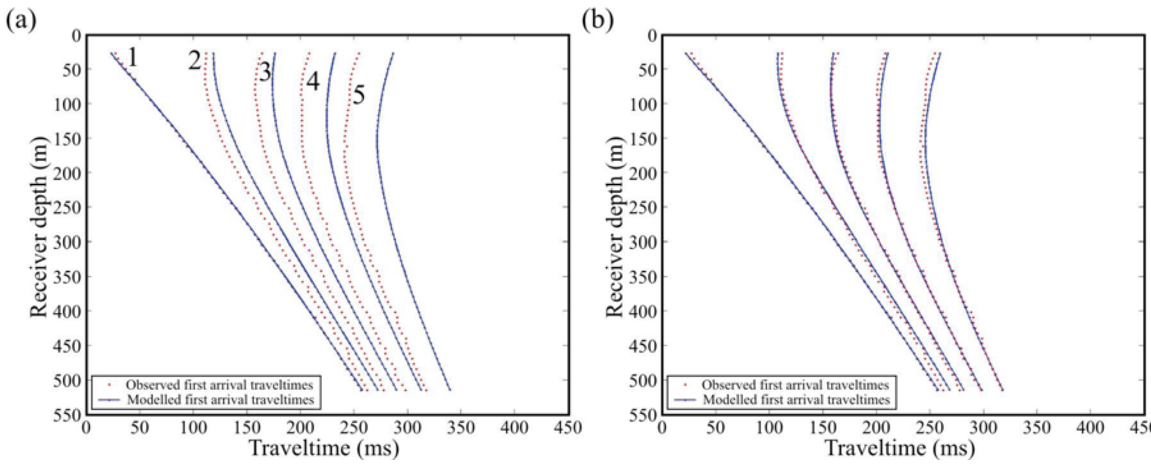

Figure 4: Observed and modelled first-arrival traveltimes for the Pike's Peak vertical velocity gradient model with (a) $\varepsilon = 0$, $\delta = 0$ and (b) $\varepsilon = 0.1$, $\delta = 0.3$. Number curves are different shot points.

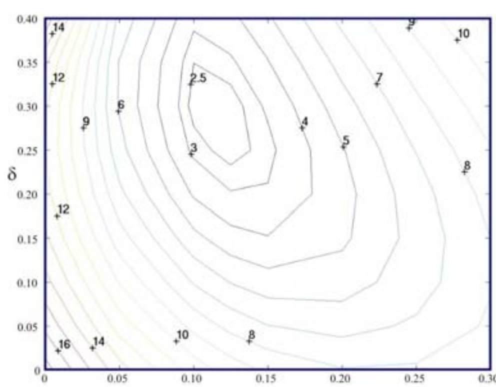

Figure 5: RMS error between the modelled and observed first-arrival traveltimes for the Pike's Peak gradient model. RMS errors are contoured in milliseconds. Global values of ε and δ were tested using $\varepsilon = 0$, 0.05, 0.10, 0.125, 0.15, 0.20, 0.25, and 0.30, and $\delta = 0$, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40.

Cygnet

The Cygnet VSP borehole is located 5 km west of Red Deer, Alberta (Figure 1) and penetrates the Palaeocene Paskapoo Formation and Ardley coal zone. The Paskapoo Formation consists of interbedded sands and shales (Dawson et al., 1994). Over the limited extent of the survey we have assumed horizontal layering.

The Cygnet VSP data were analysed using the same methodology described above to assess turning rays and anisotropy at Pike's Peak therefore only the survey parameters and results are presented here. Receivers were located down the vertical borehole, 9-34-38-28W4, from 20 m to 295 m depth (Figure 6). The zero-offset and multi-offset data were recorded with receivers located at 5 m and 15 m spacing, respectively. Source points were located along a 180° azimuth at 20 m for the zero-offset survey, and 100 m, 150 m, 191 m and 244 m for the multi-offset survey. A three-component five-level tool with receivers at 15 m spacing was used to record the VSP. The vertical component first-arrival traveltimes for the 20 m and 244 m offsets are shown in Figure 7.

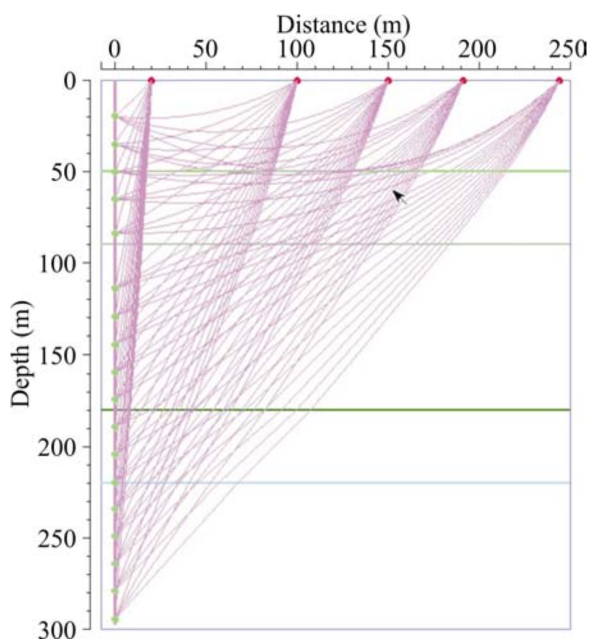

Figure 6: VSP layout for the Cygnet survey near Red Deer.

Numerical model

Initially single- and two-layer models were tested but computed first-arrival traveltimes did not match those observed in the field. A five-layer numerical model was constructed with horizontal layers defined by velocity boundaries identified in the zero-offset VSP. Zero-offset VSP and sonic log traveltimes were used to constrain the vertical velocity profile. The negative apparent slowness at shallow depths in the borehole for offset shots, and the associated reverse polarity indicated that turning rays were present. We therefore created a numerical model that contained linear vertical velocity gradients based upon the zero-offset VSP.

An isotropic solution was found to match computed and observed traveltimes well (Figure 8a). Anisotropy was added to the layers to determine whether the fit could be improved. Even with small values of ε and δ (<0.03) in the two uppermost layers the match was superior only for the longest offset (e.g. Figure 8b). ε and δ larger than 0.03 resulted in an inferior match between the calculated and observed first-arrival traveltimes.

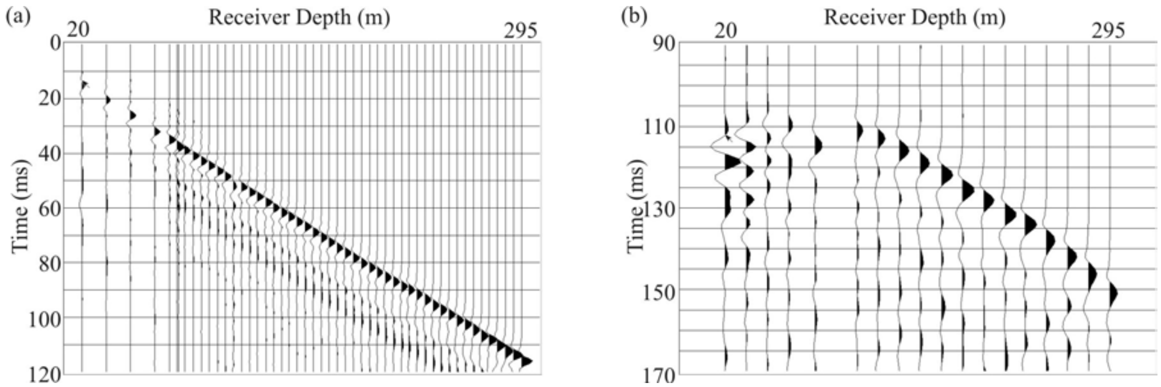

Fig. 7: Cygnet VSP first-arrival traveltimes for shot offsets (a) 20 m and (b) 244 m.

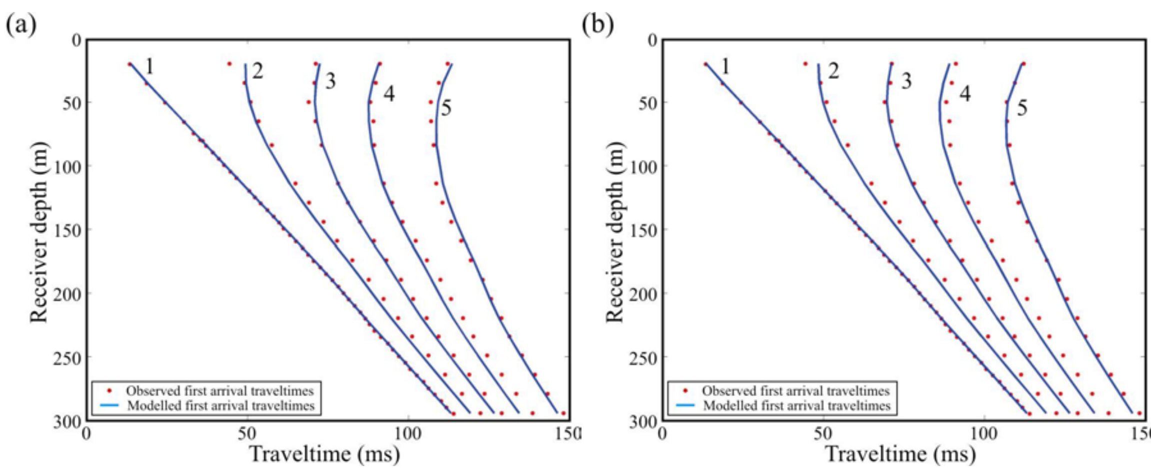

Fig. 8: Observed and modelled first-arrival traveltimes for numerical models with vertical velocity gradients with parameters of anisotropy (a) ε = 0 and δ = 0, and (b) ε = 0.02 and δ = 0.02. Number curves are different shot points.

Conclusions

Numerical modelling was used to successfully match calculated and observed first arrival traveltimes for VSPs recorded at Pike's Peak, Saskatchewan and Cygnet, Alberta. The presence of negative vertical apparent slowness and

reverse polarity first arrivals at shallow receivers in the borehole necessitated the use of vertical velocity gradients in the model.
At Pike's Peak the best fit model consisted of two layers with vertical velocity gradients of 3.1 s^{-1} and 1.2 s^{-1} respectively, and global parameters of anisotropy ε = 0.12 +/- 0.02 and δ = 0.30 -/+ 0.06.
At Cygnet an isotropic solution was found to match the observed and calculated first-arrival traveltimes well. The model consisted of five layers with vertical velocity gradients in the two uppermost layers of 10 s^{-1} and 5 s^{-1}, respectively. When anisotropy of ε = 0.02 and δ = 0.02 was added to the two upper layers of the model a better match was found for the long offset near surface traveltimes. For higher values of anisotropy the resultant match was inferior.

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