Effects of binning velocity ratios on C-wave imaging in the presence of dips

Fabio Mancini\textsuperscript{1,2}, Xiang-Yang Li\textsuperscript{1}, Anton Ziolkowski\textsuperscript{2} and Tim Pointer\textsuperscript{3}

\textsuperscript{1}British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK
\textsuperscript{2}Department of Geology and Geophysics, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, UK
\textsuperscript{3}BG Group, 100 Thames Valley Park Drive, Reading, Berkshire, RG6 1PT, UK


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Abstract

C-wave processing usually requires iterations involving velocity analysis and binning. As a first step the data are binned using a single value of $\gamma$ ($V_p/V_s$) before any P-wave independent velocity analysis, therefore sorting the data into Asymptotic Common Conversion Points. We analyse the effects of this initial binning value of $\gamma$ on C-wave imaging in areas of dipping reflectors. The data are from a 2D 4C line acquired over the Lomond field, in the North Sea. The results show that the C-wave NMO velocities in the presence of dips are sensitive to changes in the value of the binning velocity ratio. C-wave imaging relies on accurate knowledge of the effective velocity ratio $\gamma_{\text{eff}}$. This parameter is determined by a combination of the vertical and the NMO velocity ratios. Errors in the C-wave NMO velocity lead to wrong estimates of $\gamma_{\text{eff}}$. Running a pre-stack time migration prior to the calculation of $\gamma_{\text{eff}}$ reduces velocity errors due to the presence of dips. We can further improve the accuracy of $\gamma_{\text{eff}}$ by using the CCP-scanning technique.

ACCP binning, initial $\gamma$ value, $\gamma_{\text{asy}}$

As the up-going leg of the C-wave raypath (S-wave) is slower than the down-going leg (P-wave), Snell's law requires that it is reflected at a more acute angle to the normal to the interface. This means that the conversion point is generally shifted towards the receiver so that the Common Mid Point (CMP) assumption is no longer valid even for plane horizontal layers. The Common Conversion Point (CCP) position is defined not only by the acquisition geometry but also by the velocity ratio between P and S-waves ($\gamma_{\text{eff}}$). $\gamma_{\text{eff}}$ changes with depth and may change laterally. As a first approximation we can keep it constant, binning the data into Asymptotic CCP (ACCP) gathers. For convenience we use $\gamma_{\text{asy}}$ to denote this initial value of $\gamma_{\text{eff}}$. From Thomsen (1999), we have:

$$x_c = \frac{\gamma_{\text{asy}} x}{1 + \gamma_{\text{asy}}}, \quad (1)$$

$$\gamma_{\text{eff}} = \frac{\gamma_n^2}{\gamma_0}, \quad (2)$$

where $\gamma_0$ is the vertical velocity ratio extracted as the ratio of the arrival times on the zero-offset sections (P-wave and C-wave stacks) and $\gamma_n$ is the NMO velocity ratio ($v_{pn}/v_{sn}$). Equation (1) relates the CCP position ($x_c$) to the CMP position ($x$). The parameter $\gamma_{\text{eff}}$ takes into account the effects of layering induced polar anisotropy. $\gamma_{\text{eff}}$ can be also estimated by applying the CCP-scanning technique (Audebert et al, 1999). This technique is robust in the presence of strong geological structures and has the advantage of not relying directly on the values of the velocity ratios, but is based on imaging concepts, so it can be used independently of the results of equation (2).

Effects of $\gamma_{\text{asy}}$ on C-wave NMO velocities

The initial C-wave velocity analysis is run on ACCP gathers. To check the sensitivity of the C-wave NMO velocity ($v_{\text{cm}}$) to $\gamma_{\text{asy}}$, we picked velocities after binning the data with different values of $\gamma_{\text{asy}}$. We separated the positive and negative offsets before picking, because diodic velocity effects are present in the Lomond Field (Mancini et al., 2002). The resulting velocity fields for the positive offsets are shown in Figure 1. On the left-hand side the C-wave positive offset stacks is shown for reference. The $\gamma_{\text{asy}}$ used were 1.25, 2.00 and 2.75. As $\gamma_{\text{asy}}$ increases, the seismic line is "squeezed"
toward the receivers, the minimum in the velocity field induced by the gas (from ACCP 800) becomes smaller, the whole velocity field appears smoother, and the lateral difference in velocity decreases. It can be seen that the greatest changes occur in the zone around 5000 ms and CCPs 600-750. This is where the dips are greatest. The presence of dips makes velocities dependent on $\gamma_{\text{eff}}$. Where dips are negligible velocities are not sensitive to changes in $\gamma_{\text{eff}}$, Dai and Li (2002).

Figure 1: C-wave positive offset stack and velocity fields for different values of $\gamma_{\text{asy}}$. From left to right the binning values are 1.25, 2.00, 2.75.

This change of shape in the velocity field is important when we calculate $\gamma_{\text{eff}}$ using equation (2), as $v_{\text{cn}}$ is used for the calculation of $\gamma_n$. Equation (2) also requires $\gamma_0$. To extract $\gamma_0$ we have to correlate the events from the same reflector on the stacked P and C-sections, which gives the vertical arrival times for P and C-waves, $t_p0$ and $t_c0$. This step is always subjective and could be a big source of errors. Well log information could supply $\gamma_0$ at a well location when a dipole shear log is acquired, but the results have to be carefully considered as shear logs in deviated wells are often unreliable (Leaney et al., 2000; Mancini et al., 2002).

Sensitivity analysis

To gain more insight into the effects of $\gamma_{\text{eff}}$ on $v_{\text{cn}}$, we calculated the velocity values at $t_c = 5000$ ms (reservoir depth in C-wave time) for the positive offsets, resulting from velocity analysis on ACCP gathers binned with different values of $\gamma_{\text{asy}}$: 1.25, 2.00 and 2.75. Given $v_{\text{cn}}$ and $v_{\text{pn}}$ form P-wave processing we then calculated the values of $\gamma_n$ and $\gamma_{\text{eff}}$ at the same arrival time, using a constant $\gamma_0 = 2.80$ (obtained from event correlation) and the S-wave NMO velocity, calculated as follows

$$v_{\text{sn}}^2 = v_{\text{cn}}^2 \left(1 + 1/\gamma_0\right) - \frac{v_{\text{pn}}^2}{\gamma_0}. \quad (3)$$

We quantify changes in $v_{\text{cn}}$, $\gamma_n$ and, $\gamma_{\text{eff}}$ using their ratios. Figure 2 summarises the results. The x-axis is the ACCP number, the y-axis is the ratio. The results for the velocity show a maximum velocity change of about 5% for a 37.5% change in $\gamma_{\text{asy}}$. For $\gamma_{\text{asy}} = 1.25$ and 2.00, ($\gamma_{\text{asy}}$ relative change of 60%), the maximum $v_{\text{cn}}$ change increases slightly, up to 7%. The difference is higher on the sides, where we have steep dips, and lower in middle of the 2D line.

$\gamma_n$ and $\gamma_{\text{eff}}$ change in the opposite direction to $v_{\text{cn}}$. The magnitude of the change increases from $v_{\text{cn}}$ to $\gamma_n$ to $\gamma_{\text{eff}}$. There is a 23% change in $\gamma_{\text{eff}}$ for a 5% change in $v_{\text{cn}}$ and there is a 31% change in $\gamma_{\text{eff}}$ for a 7% change in $v_{\text{cn}}$. For minor variations in $v_{\text{cn}}$ less than 2%, the change in $\gamma_{\text{eff}}$ is within 10%. We can also notice that, as the salt dome structure shifts from left to right for higher values of $\gamma_{\text{asy}}$ (confront Figure 1), the position of the area of minimum change shifts as well. These results show how small changes in $v_{\text{cn}}$ have a great effect on the calculation of $\gamma_{\text{eff}}$. If the resulting value of $\gamma_{\text{eff}}$ differs significantly from the $\gamma_{\text{asy}}$ used for velocity analysis, new velocity analyses after more appropriate binnings are necessary.
Figure 2: Relative changes in $v_{cn}$, $\gamma_n$ and $\gamma_{eff}$ for different $\gamma_{asy}$. (a) The blue line is for $v_{cn}(1.25)/v_{cn}(2.00)$, the purple line is for $\gamma_n(1.25)/\gamma_n(2.00)$ and the yellow line is for $\gamma_{eff}(1.25)/\gamma_{eff}(2.00)$. (b) Same colours as in (a) for $v_{cn}(2.00)/v_{cn}(2.75)$, $\gamma_n(2.00)/\gamma_n(2.75)$ and $\gamma_{eff}(2.00)/\gamma_{eff}(2.75)$.

**Estimating $\gamma_{eff}$: DMO vs. PSTM**

Equation (2) is based on plane horizontal layers. Before using equation (2) we should minimise the effects of dip in the data. We consider separately the effects of DMO and pre-stack time migration (PSTM). Figure 3 shows two diagrams for $\gamma_{eff}$, one after DMO, and one after PSTM. The original $\gamma_{asy}$ used for the ACCP binning was 1.50 in both cases. On the left-hand side the P-wave stack is shown for structural reference. Both $\gamma_{eff}$ diagrams are shown in P-time. After DMO the resulting $\gamma_{eff}$ is too low, even less than 1 on the sides of the structure. This implausible result is caused by the anomalously high C-velocities obtained on both flanks of the salt dome, where the dips are highest. The high values of P-velocities due to the salt are also clear. DMO does not adequately correct for the effects of dip for the converted waves. After PSTM $\gamma_{eff}$ is generally higher and more physically acceptable: on the flanks of the salt dome the value ranges from 1.2 to 1.4, while on top of the dome it ranges from 1.6 to 1.8. The minima caused by the dips are now reduced.

Figure 3: Left: P-wave stack, middle: values of $\gamma_{eff}$ calculated using equation (2) after DMO, right: the same after PSTM. Even after DMO the effects of the dips are clearly visible in the areas of low $\gamma_{eff}$. After PSTM these effects are reduced. The colour scale is the same.

**CCP-scanning technique**

The CCP-scanning technique can be used as an independent tool to extract $\gamma_{eff}$. We apply it in the time domain (Li et al, 2001), binning the positive and negative offsets with different values of $\gamma_{asy}$, looking for the value which gives better image focusing and less (or no) lateral shift in the geological structure. We used values of $\gamma_{asy} = 1.25, 1.50, 1.75, 2.00$, Figure 4. As $\gamma_{asy}$ increases, the salt dome shifts toward the right (higher ACCP numbers) for the positive offset image and towards the left for the negative one. The negative offset image appears to be disturbed by the presence of gas and this makes the interpretation slightly more difficult. The correct value of $\gamma_{asy}$ seems to be between 1.50 and 1.75, which agrees which the value of $\gamma_{eff}$ given by equation (2) after PSTM.
In difficult areas for velocity analysis, such as those affected by gas clouds or severe dips, the use of the CCP-scanning technique becomes a necessary step (Li et al., 2001). Its use as the first tool for estimating $\gamma_{\text{eff}}$ can reduce the risk of errors and the need for more iterations.

**Figure 4:** Positive (top ones) and negative offsets binned with different values of $\gamma_{\text{asy}}$, from left to right: 1.25, 1.5, 1.75, 2.0. The value that creates the best structural alignment for two offsets is between 1.5 and 1.75.

**Discussions and conclusions**

In areas affected by dip $v_{\text{cn}}$ is sensitive to changes in $\gamma_{\text{asy}}$, the initial value of $\gamma_{\text{eff}}$. Then, small errors in the value of $v_{\text{cn}}$ are propagated as the square in the calculation of the next estimate of $\gamma_{\text{eff}}$ and cannot be ignored as they can lead to unrealistic values of $\gamma_{\text{eff}}$. We have found that the effect of dip can be reduced significantly by running PSTM on ACCP gathers. It is advantageous to run it prior $\gamma_{\text{eff}}$ estimation. Some positioning errors could still remain if the original binning value is not correct. The CCP-scanning technique is a robust tool that should also be used in order to improve the estimation of $\gamma_{\text{eff}}$.

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**References**


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