Compensating for the effects of gas clouds on C-wave imaging: A case study from Valhall

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P-to-S converted waves (or C-waves) have been successfully used to image beneath gas clouds in many areas. However, C-waves often suffer from severe diodic effects due to the gas clouds; that is, the C-wave amplitude and traveltime may be different in the forward and reverse shooting directions, giving rise to different C-wave stacking velocities (diodic $V_C$) and velocity ratios (diodic $\gamma_{\text{eff}}$). In some cases, whether a horizon (a geologic target) beneath a gas cloud can be undershot also depends on the shooting directions (diodic illumination). These effects, compounded with the asymmetric raypath of the C-wave and the uncertainties in the P-wave data due to the gas clouds, will further increase the difficulties and costs of processing C-wave data. In this article, using the 2-D Valhall data as an example, we examine these effects and discuss ways to compensate for them during processing for improving the C-wave imaging.

**Effects of gas clouds.** The 2-D Valhall data were acquired in 1996. In the survey area, the overburden layers are highly charged with gas. These gas clouds are not thought to be present in economic quantities, but they attenuate the P-wave energy substantially and reduce the P-wave velocity, inducing dimming and push-down effects on the P-wave data (Figure 1a).

The presence of gas usually has a small effect on the shear modulus. Hence, S-waves are much less affected by gas than P-waves. This forms the basis for the use of P-to-S converted waves (C-waves) for imaging beneath gas clouds. However, the amplitude of the converted waves is critically dependent on whether the downgoing P-waves pass through the gas clouds. For example, at the edge of the gas clouds (Figure 2), depending on the forward or reverse shooting direction, positive (+) or negative (-) offsets, the P-wave may or may not go through the gas clouds. On one hand, if the P-wave leg goes through the gas clouds (-offset, Figure 2), the resultant C-wave will be very weak or absent; on the other hand, if the P-wave leg does not go through the gas cloud (+offset, Figure 2), the resultant C-wave will be very strong. This is referred to as the diodic illumination effect. Figure 3a shows an example of this effect from the Valhall data. The events marked by the white arrows in the positive offset show strong amplitudes, but they fade in the negative offset. If the gas clouds are small and represent mild velocity variations, horizons (or targets) beneath the gas clouds will still be illuminated by shooting in both directions, but it will result in different stacking velocities ($V_C$). This is referred to as diodic $V_C$. Due to diodic $V_C$, the moveout cannot be corrected using a single set of $V_C$ for both negative and positive offset data (Figure 3b). Careful processing is required to compensate for these diodic effects.

**Compensating methods.** In addition to $V_C$, C-wave processing is also determined by the vertical P- and S-wave velocity ratio $\gamma_0$ and the effective velocity ratio $\gamma_{\text{eff}}$ in inhomogeneous media. The situation is further complicated in the presence of anisotropy; this is beyond the scope of this article. A typical C-wave
Figure 3. Common-conversion-point (CCP) gathers from the Valhall data showing the diodic effects. (a) Diodic illumination at CCP 1250. The events (white arrows) show strong amplitude in the +offset panel, but weak amplitude in the -offset panel. (b) Diodic \( V_C \) at CCP 950. The events show high velocity in the -offset panel and low velocity in the +offset panel. The moveout is corrected using the high velocity.

Figure 4. Comparison of C-wave velocity analyses at CCP gather 1250. (a) Nonhyperbolic velocity analysis over offsets twice the reflector depth and (b) hyperbolic short-spread velocity analysis over offsets equal to the reflector depth.

processing flow may have the following four steps: (1) \( \gamma_0 \) analysis, (2) \( V_C \) analysis, (3) \( \gamma_{\text{eff}} \) analysis, and (4) prestack migration. To compensate for the effects of gas clouds in improving C-wave imaging, there are three key elements in the implementation of the above flow. First, to compensate for the diodic effects, it is natural to separate the data into positive-offset (+) and negative-offset (-) data volumes, and then process these two volumes of data separately. Second, it is necessary to determine \( \gamma_{\text{eff}} \) from C-wave data alone by a data-driven approach that is independent of the P-wave data. This is because the P-wave velocity \( V_p \) is often unreliable in the presence of gas clouds, and a joint P- and C-wave processing scheme will degrade the C-wave data. Third, in the presence of gas clouds, it is clear that C-wave processing requires an iterative processing scheme due to the need for independent processing, and also due to the dependency of the C-wave imaging point on the velocity ratio \( \gamma_{\text{eff}} \). We now use the Valhall data to illustrate these ideas.

\( \gamma_0 \) analysis. In the absence of borehole data, the only way to obtain the vertical \( V_p/V_s \) ratio \( \gamma_0 \) is by correlating the P- and C-wave stacked sections. Fortunately the C-wave traveltimes are not very sensitive to the variations in \( \gamma_0 \), and consequently a coarse correlation is often sufficiently accurate. To obtain the initial sections for correlation, the P- and C-wave data are processed using only standard hyperbolic methods. Because P-wave processing is independent of the C-wave, the final P-wave imaging may be used for correlation. For the C-wave data, the initial processing flow often contains asymptotic common-conversion-point (ACCP) binning, hyperbolic velocity analysis, NMO correction, DMO correction, stack, and migration. Figure 1 shows the correlated events. An average \( \gamma_0 \) function with coarse intervals is obtained from correlation and is then used for subsequent processing (Table 1).

\( V_C \) analysis. C-wave moveout is inherently nonhyperbolic due to the asymmetric raypath. This often gives rise to 3-5% errors in \( V_C \) obtained by a hyperbolic procedure, even for

<table>
<thead>
<tr>
<th>( t_{\text{PV}} ) (sec)</th>
<th>( t_{\text{P}} ) (sec)</th>
<th>( \gamma_0 )</th>
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<td>3.1</td>
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noise-free data. Error propagation is a severe problem in estimating C-wave processing parameters. For typical North Sea sediments with a velocity ratio of 3.0, a moderate 3% error in $V_C$ results in more than 15% error in estimates of $\gamma_{dir}$ which may invalidate the whole processing sequence. Thus, reestimating $V_C$ is necessary to correct for the nonhyperbolic effects. This is achieved by adding a nonhyperbolic term into the existing hyperbolic equation. The new equation is a function of both $V_C$ and $\gamma_b$. Because $\gamma_b$ has been determined from the previous step, this equation can then be used to perform nonhyperbolic $V_C$ analysis for offsets up to twice the reflector depth. Figures 4 and 5 compare the effectiveness of nonhyperbolic $V_C$ analysis. The nonhyperbolic velocity spectrum is more focused than the hyperbolic spectrum. In the shallow section above 3.0 s, the nonhyperbolic spectrum shows clear velocity picks (Figure 4a) and the hyperbolic spectrum shows either no or erroneous picks. The corresponding events in the resulting common-imaging-point (CIP) gather using the $V_C$ from Figure 4a are properly aligned (Figure 5a), but those in the CIP gather using the $V_C$ from Figure 4b are undercorrected (Figure 5b).

Figure 5. Comparison of CIP gathers at 1250 obtained from prestack Kirchhoff time migration using (a) nonhyperbolic $V_C$ in Figure 4a and (b) hyperbolic $V_C$ in Figure 4b.

Figure 6. Examples of focusing analysis for the shallow horizons (0.5-2.0 s). The two images with a $\gamma_{eff}$ of 2.5 have the best quality and the events in both offset domains are similar and well focused. The first row is for the positive-offset data, and the second row is for the negative-offset data. The results of $\gamma_{eff}$ values 2.2, 2.5, and 2.8 are displayed.

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Figure 7. The same as Figure 6 except for the target horizons (4.5-6.0 s). The two images with a $\gamma_{\text{eff}}$ of 2.2 have the best quality, and the events in both offset domains are similar and well focused.

Figure 8. The velocity models obtained for the Valhall data. (a) and (b) are, respectively, the $V_C$ and $\gamma_{\text{eff}}$ obtained from the C-wave data alone, and (c) and (d) are the $V_P$ and $V_S$ calculated from $\gamma_{\text{eff}}$ and $V_C$. The vertical times are all in C-wave two-way times.

$\gamma_{\text{eff}}$ analysis. $\gamma_{\text{eff}}$ is often determined by a joint inversion of the $P$- and C-wave stacking velocities. The presence of gas clouds introduces severe uncertainty in the $P$-wave stacking velocity ($V_P$). To minimize the effects of this uncertainty, a CCP scanning technique based on focusing analysis is proposed to determine $\gamma_{\text{eff}}$ from C-wave data alone. This method uses different $\gamma_{\text{eff}}$ to bin the C-wave data and process them accordingly (CCP scanning). The optimum $\gamma_{\text{eff}}$ is determined by comparing the focusing quality between the +/- offset data volumes. This is illustrated in Figures 6 and 7. Figure 6 shows the CCP scan-
Figure 9. Final prestack-migrated imaging of the C-wave from the Valhall data. (a) Negative offset data, (b) positive offset data, and (c) the combined imaging.

Figure 10. Results of the Mahogany 2-D-4-C data. (a) and (b) are, respectively, the poststack- and prestack-migrated C-wave sections. We applied the same processing sequence as that used for the Valhall data.

determined, then \( V_p \) and \( V_s \) are also determined. Thus it is possible to ignore the \( V_p \) determined from the \( P \)-wave data and to meet the requirement of the compensation method.

It is common practice to update the velocity models during migration. Updating is achieved by analyzing the residual moveout in the CIP gathers. We find that updating \( V_C \) alone is often sufficient. Also, the \( V_C \).
determined by the nonhyperbolic analysis is often sufficiently accurate for migration (Figure 5a).

Valhall and Mahogany results. We apply the above approach to the Valhall C-wave data. Figures 8a and 8b, respectively, the $V_C$ and $\gamma_{\text{eff}}$ obtained from the C-wave +/- offset data, and Figures 8c and 8d show the calculated $V_P$ and $V_S$. Note that there are significant differences between the +/ - offset data in $V_C$ and $\gamma_{\text{eff}}$, indicating the dodiic effects. However, the differences between the +/ - offsets for the calculated $V_P$ and $V_S$ are relatively small.

Figures 9a and 9b show the final migrated results for the +/- offsets, respectively. The two images are quite different in the target area (between 5 and 6 s) due to the dodiic illumination effect caused by the gas clouds. For example, dimming events appear in the middle right part of Figure 9a (-off-rate data), while the corresponding dimming events appear in the middle left part of Figure 9b (+offset data). The final migrated result can be obtained by adding the two images together (Figure 9c).

Comparison of Figure 9c with Figure 1b shows that the prestack migrated section is better focused. In the target area between 5 and 6 s, the fault blocks underneath the gas clouds are well imaged. In contrast, smearing in the poststack-migrated section is evident (Figure 1b), particularly in the target area. The events above the target area in Figure 9c are also more continuous than those in Figure 1b.

To further verify the above scheme, we have also applied the same processing to the Mahogany data set, which also leads to improved C-wave imaging (Figure 10). Note that the Mahogany data set was distributed to several institutes by the workshop organizer to evaluate the different C-wave processing strategies used in the geophysical community.

Conclusions. In this article, we have examined the dodiic effects of the gas clouds on C-waves using the Valhall data and have developed a practical processing scheme to compensate for these effects. The key steps are offset separations, nonhyperbolic velocity analysis, CCP scanning, and prestack migration. The basic idea is to determine the processing parameters $V_C$ and $\gamma_{\text{eff}}$ from C-wave data alone and independent of P-waves. The final result shows better imaging under the gas clouds compared with those using conventional methods. Application to the Mahogany data reconfirms the methodology.