Special section: Thin beds

Tuning of flat spots with overlying bright spots, dim spots, and polarity reversals

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Abstract

Reflection seismic data from block F3 in the Dutch North Sea exhibit many large-amplitude reflections at shallow horizons typically categorized as bright spots. In most cases, these bright reflections show a significant “flatness” that contrasts with local structural trends. Although flat spots in thick reservoirs are often easily identified, others within thin beds or near reservoir edges can be difficult to identify and are poorly understood. Many of the shallow large-amplitude reflections in this block are dominated by flat spots. We investigated the tuning effects that such flat spots cause as they interacted with reflections from the top of the reservoir. We first studied the zero-offset “wedge-model” tuning effects of the flat spot with overlying bright spots, dim spots, or polarity reversals. We then expanded that model to examine prestack tuning effects, as well as the results from inclusion of postcritical flat spot reflections in the final stack. We observed that under certain conditions, the reflections could appear to be somewhat flattened bright spots; those conditions might be met frequently in practice, and they should be considered in routine interpretation. In the North Sea case, we concluded that this tuning effect was the primary cause of the brightness and flatness of these reflections.

Introduction

Observations of flat bright spots

Direct hydrocarbon indicators (DHIs) have long been used successfully in exploration projects (Brown, 2012). Bright spots, for example, demonstrate an increase in (negative) reflection coefficients as the water sand beneath a higher impedance cap rock transitions to a gas sand or oil sand. These changes can be recognized easily and are often exploited because of their prominence in a seismic section. Flat spots that represent reflections from the hydrocarbon-water contact are also easy to recognize because of their unconformable flatness, and they are always positive in sign. Dim spots result from a cap rock that is of lower impedance than the underlying water sand and hydrocarbon sand. Brown (2012) emphasizes that dim spots may represent overlooked exploration targets because of their unconformable flatness, and they are always positive in sign. Dim spots result from a cap rock that is of lower impedance than the underlying water sand and hydrocarbon sand. These are presumably difficult to recognize for the same reasons as dim spots.

We present an interesting case study from offshore Netherlands block F3, which leads us to more general observations. The area exhibits significant bright reflections that are very flat in nature, contrasting with the structural trend of the surrounding rocks. The data set used for this work (provided by dGB Earth Sciences for use with the OpendTect software suite) includes poststack 3D seismic data with limited well-log data from four wells. This data set also demonstrates excellent examples of gas chimneys, DHIs, and stratigraphic features. Of interest in our study are small shallow uneconomic reservoirs that exhibit very bright and flat reflections. Figure 1 shows one example of these reservoirs. Throughout this paper, we will focus on this specific reservoir, considering it to be representative of other nearby reservoirs that exhibit the same phenomenon. Note the brightness of the reservoir reflections marking the top of the reservoir. It is this bright nature of these reflections that has led to their categorization as bright spots in the literature (Schroot and Schuttenhelm, 2003).

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To estimate the departure of this reflection from the structural trend, we compared it with immediately overlying layers. The green line in Figure 1 shows a tracked horizon indicative of the structural trend. A phantom horizon was created from the green horizon by shifting it downward an appropriate time. This phantom horizon is displayed in blue below the tracked horizon. Although the phantom horizon is conformable with the water-sand reflections along the flanks, it is not conformable with the bright reflections associated with the gas reservoir at the crest. This observation suggests that the “red” reflections (negative, indicating an acoustic impedance decrease) are not simple bright spots, but they are influenced by the underlying flat spot. The flatness and the brightness of the reservoir reflections need to be explained if we are to properly interpret similar features elsewhere.

**Basic techniques used in this study**

To examine these flat and bright features, we created synthetic data from different models. We examined tuning effects for normal incidence on thin hydrocarbon beds. Then, we examined nonnormal incidence pre-stack tuning and the effect of postcritical phase shifts on stacking.

The shallow layers in block F3 consist of alternating beds of shale and sand. Tuning effects are often observed in thin beds (Ricker, 1953; Widess, 1973; Kallweit and Wood, 1982; Chopra et al., 2006). The reservoirs under discussion exhibit features that suggested to us that tuning plays an important role in the generation of these flat reflections. Most tuning models consider reflections from the top and bottom of sand layers. Here, we expect this tuning to arise from the reflections from the top of the reservoir and the flat spot reflection at the gas/water contact (GWC). First, we examine this issue from a normal incidence assumption, as is done in most thin-bed studies.

We also examine the effect of amplitude variations with offset or angle (AVO), and we include postcritical reflections in our models. The effect of postcritical reflections is usually not considered for stacking purposes, but these (uneconomic) reservoirs lie at very shallow depths (~500 m), and it is very likely that postcritical reflections have been recorded. These postcritical reflections may or may not have been muted prior to stacking. Postcritical reflections involve a phase shift, and if these reflections are included in the stacking process, the wave shape and amplitude of the final stacked event will change. In addition, these rocks are highly unconsolidated and the elastic properties of the rocks will be strongly influenced by the nature of the pore fluid (e.g., Hilterman, 2001). Therefore, we expect to observe a large velocity contrast at the GWC. This, in turn, will result in a small critical angle for flat spot reflections.

The work involved four basic steps. First, we undertook simple rock-physics modeling to estimate several unknown formation properties needed for analysis. Then, we conducted forward seismic normal-incidence modeling to study possible tuning effects. The third step involved AVO analysis and the effect of postcritical reflections. Finally, we investigated the AVO influence on the overall stack with and without normal moveout (NMO) stretch and muting. We conclude that thin-bed tuning effects of DHIs (particularly dim spots and polarity reversals) with their underlying flat spots may result in flat bright reflections that one may interpret as bright spots.

**Methodology**

In this section, we first provide the methodology used in our study, and then we apply it to a model designed to resemble the lithology present in North Sea block F3.

**Tuning effects for normal incidence**

Ricker (1953), Widess (1973), Kallweit and Wood (1982), and Chopra et al. (2006) study tuning effects in detail and establish tuning thicknesses and resolvable limits. Widess (1973) concludes that for bed thicknesses thinner than half of the seismic wavelength (λ/2, where λ is the dominant wavelength), the reflections from the top and bottom of the layer interfere in ways that change the shape and amplitude of the wavelet. As the bed thins to one-fourth of the wavelength (λ/4), the amplitude of the tuned wavelet grows and reaches a maximum through the constructive interference of the side and main lobes of the two reflections. This thickness is called the tuning thickness. When the bed thickness reaches one-eighth of the wavelength (λ/8), the composite wavelet resembles a derivative of the original waveform and no change in trough-to-peak time will be observed. The amplitude then decreases toward zero as the bed continues to thin
Widess (1973; Kallweit and Wood, 1982). Widess (1973) points out that a thin-bed thickness should be at least one eighth of the dominant wavelength to be delineated. However, in the presence of noise, the resolution is usually taken to be $\lambda/4$ (Chopra et al., 2006).

Most of these studies used a wedge model similar to that shown in Figure 2, with a seismic section (Figure 2a) and tuning curve (Figure 2b). In this case, a 50-Hz (dominant frequency) Ricker wavelet was convolved with opposite but equal reflection coefficients at the upper and lower interfaces. Some published examples (e.g., Robertson and Nogami, 1984) used reflection coefficients that are identical rather than opposite in polarity.

In our case, however, we are interested in a different sort of wedge model, shown in Figure 3. This model is more appropriate for a wedge of hydrocarbon sand between overlying shale and underlying water sand. Many characteristics of the conventional wedge model are seen here. In contrast to a conventional wedge model, the polarity of the overlying shale-sand interface may differ from the polarity of underlying flat spot. The difference in polarity occurs when the impedance of the gas sand is lower than the impedance of the overlying shale. Detailed physical properties of the rock matrix, pore-fluid, and composite rocks used in modeling are given in Tables 1–3.

**Tuning effects for amplitude variation with offset**

Rutherford and Williams (1989) group AVO responses into three classes (I–III) based on normal incident reflection coefficient and AVO behavior, whereas Castagna et al. (1998) add an additional class IV. Some other authors have identified additional “classes,” but most authors refer only to these four. Another important type of AVO behavior is exhibited by all flat spots (see the following paragraph), but it is generally not given its own classification. Figure 4 shows the four

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**Figure 2.** (a) Synthetic wedge model (indicated by the blue lines), with reflection coefficients that are negative at the dipping upper interface and positive at the lower flat interface, convolved with a 50-Hz Ricker wavelet. (b) Amplitude (blue line) and trough-to-peak time (green line) of the composite wavelet as a function of bed thickness.

**Figure 3.** (a) The normal-incidence responses for the structural model we are interested in, in which a wedge of hydrocarbon-saturated rock is overlain by a sealing shale and underlain by a water-saturated rock (interfaces are indicated by blue lines). We use a polarity-reversal case in this example. (b) Amplitude of reflections from the dipping interface, where a bright negative reflection occurs over the hydrocarbon-saturated rock at tuning thicknesses, contrasted with the smaller positive reflection over the water-saturated rock. Notice the change of amplitude due to the tuning and the polarity reversal at the termination of the hydrocarbon wedge.

**Table 1. List of all parameters used in rock-physics modeling.**

<table>
<thead>
<tr>
<th>Formation properties (from well logs)</th>
<th>Fluid properties</th>
<th>Grain properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_p$ (m/s)</td>
<td>$K_w$ (GPa)</td>
<td>$K_{grain}$ (GPa)</td>
</tr>
<tr>
<td>2343</td>
<td>2.20</td>
<td>37.00</td>
</tr>
<tr>
<td>$V_p$ (m/s)</td>
<td>$\rho_w$ (kg/m$^3$)</td>
<td>1.10</td>
</tr>
<tr>
<td>2056</td>
<td>1.10</td>
<td>2.65</td>
</tr>
<tr>
<td>$\phi$ (%)</td>
<td>$K_g$ (GPa)</td>
<td>$\rho_{grain}$ (kg/m$^3$)</td>
</tr>
<tr>
<td>38</td>
<td>0.01</td>
<td>2.65</td>
</tr>
<tr>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\rho_{gas}$ (kg/cm$^3$)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0.10</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
classic AVO classifications plus the AVO behavior of flat spots.

Most bright spots exhibit class III AVO behavior; that is, they exhibit a negative reflection at zero offset ($R_n$) that increases (negative) with increasing offset. These are the most-often cited DHIs, and they are often easily recognized.

For most dim spots, class I (or II) AVO characteristics are observed. They exhibit a positive $R_n$ and decreasing positive amplitude with increasing offset, perhaps eventually becoming negative. Because the dim spot classification is based on stacked images, the stack must still be positive even if the amplitudes at far offsets are negative.

All flat spots exhibit similar behavior, in which the reflection is always positive and its amplitude increases with offset. This is because the effect of fluid substitution in a given reservoir rock will always result in low acoustic impedance (hydrocarbon zone) over high acoustic impedance (water zone). Because the shear modulus is unchanged, the negligible change in shear velocity across the interface is due only to the density effect. In most classification systems, this flat spot behavior is not recognized as a distinct class.

Because the amplitudes of the offset traces contribute to the amplitude of the final stack, it is important to consider those amplitudes in interpreting the final stack. This is often ignored when the stack is treated, as it often is, as an acoustic or zero-offset section. In this study, we examine this effect and its significance for tuning.

**Normal moveout correction, stretch, and muting**

In addition to AVO, the final stack can be impacted by the changes in wavelet shape with offset that result from stretching and phase shifts. Stretching can occur as a result of NMO correction, and phase shifts occur naturally in postcritical reflections.

The amount of extra traveltime ($\Delta t_{\text{NMO}}$) due to NMO for reflections observed at nonzero offset can be readily observed and computed (Buchholtz, 1972). Because conventional NMO correction uses different values of $\Delta t_{\text{NMO}}$ at different two-way reflection times, the result is a distortion of the wavelet. This distortion is more pronounced for early times and long offsets, and includes a reduction in high-frequency content (Shatilo and Aminzadeh, 2000). Buchholtz (1972) points out that the most severe stretching of the wavelet occurs at the intersections of reflection hyperbolas.

The usual solution for the NMO stretch problem is to discard or mute the severely stretched part of the traces, dependent on time and offset (Buchholtz, 1972). Usually a stretch limit of 50% (occasionally up to 100%) is taken to determine the muting zone of the CMP gather.

**Rock-physics modeling**

The tuning models described above are applied to the case of the flat bright events in North Sea block F3. In this section, we review the rock-physics components of the model.

**Rock properties**

The location of the (uneconomic) gas reservoir of interest is inline 210–250, crossline 1050–1200 at a depth of 520–560 ms in the survey from block F3 of the Dutch North Sea. None of the four wells drilled in the block penetrated this reservoir, but a nearby well (F03-4) provides data for the water-saturated equivalent sand as well as for the overlying shale. Figure 5a shows the well

<table>
<thead>
<tr>
<th>Table 2. Results of the rock-physics modeling.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Shale</td>
</tr>
<tr>
<td>Gas sand  (Gas saturation = 80%; porosity = 38%)</td>
</tr>
<tr>
<td>Water sand</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3. Hypothetical models for the three different hydrocarbon indicators, varying only the shale properties. The polarity reversal is modeled after the log data for the well used, and the other cases are modified from that.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright spot</td>
</tr>
<tr>
<td>Overlying shale</td>
</tr>
<tr>
<td>$V_p = 2380$ m/s</td>
</tr>
<tr>
<td>$V_S = 966$ m/s</td>
</tr>
<tr>
<td>Gas sand</td>
</tr>
<tr>
<td>Water sand</td>
</tr>
</tbody>
</table>
location and identifies the water-saturated sand with respect to the reservoir. This well has only gamma-ray (GR) and sonic logs available at this depth. The sonic velocities for the overlying shale and water sand were obtained from the well logs (Figure 5b). The fluid and grain properties were assumed from standard fluid and mineral properties. All of these properties are listed in Table 1. The sonic log indicates that the overlying shale has a lower compressional velocity than the water sand. Neglecting the density differences across the interfaces, the sonic measurements imply that the gas zone should not exhibit a bright spot, but it should display a polarity reversal or a dim spot. In the following section, we will see that simple fluid substitution further suggests that the gas zone should exhibit a polarity reversal (positive reflection over the water sand and negative reflection over the gas sand), rather than a dim spot.

**Rock-physics modeling results**

To overcome the limited log data available, we used Gardner et al.’s (1974) law to estimate density and Greenberg and Castagna’s (1992) model for the shear velocities of the water sand and the shale. We then used the Gassmann (1951) equation for fluid substitution in the sand, assuming 80% gas saturation and normally pressured gas typical of this depth.

The results from Gassmann fluid substitution are shown in Figure 6. The formation is very sensitive to pore fluid, and replacement of water with gas decreases the impedance dramatically. The results of this rock-physics modeling are tabulated in Table 2. Having estimated the rock properties, forward modeling studies were conducted to study the possible tuning effects and are presented in the following sections.

**Tuning effect analysis at normal incidence (zero-offset)**

**Normal-incidence models**

To generalize beyond our specific case, the normal-incidence tuning effect was analyzed with three different models using only one variable: the acoustic impedance of the overlying shale. That is, using the properties observed for the water sand in block F3 and our calcu-

![Figure 4. The four usual AVO classifications defined by Rutherford and Williams (1989), Castagna et al. (1998), and typical flat spot behavior.](image)

![Figure 5. (a) A stacked seismic section from the F3 Block showing well (F03-4) location and water-saturated sand with respect to the reservoir location. The log displayed is the GR log, and the values shown range from 0 (near the well-track) to 90 API (away from the well track). (b) GR and sonic logs in detail around the water-saturated sand from 500 to 630 ms depth (tracked horizons: red and green lines indicate the top and bottom of the wet sand, respectively).](image)

![Figure 6. Results of substituting water-saturated sand with gas-saturated sand by the Gassmann equation using parameters defined in Table 1, and $V_S$ of water-saturated sand as estimated by Greenberg and Castagna’s (1992) model and given in Table 2.](image)
lated properties for the gas sand, we varied the properties of the overlying shale to model a (1) bright spot over a flat spot, (2) polarity reversal over a flat spot, and (3) dim spot over a flat spot. Details are provided in Table 3.

A geologic wedge model was used for tuning analysis, with an upper interface dipping at 0.36 ms/trace. A zero-offset synthetic seismic section was generated by convolving a 50-Hz Ricker wavelet (approximating the spectrum of the original seismic data) with the geologic model (Figure 7). Figure 8 shows the synthetic seismograms generated for all three cases. The red lines follow the negative (trough) reflections in the region where the tuning effect has distorted the wavelets, whereas the blue lines show the actual boundary of the wedge model. Note that in some cases, we show red lines away from the tuning effect to emphasize possible confusion from poorly tracked events.

**Tuning effect on zero-offset sections**

The top model in Figure 8 shows the synthetic seismograms for the polarity-reversal case. In this model, the shale impedance is less than that of water sand but greater than that of gas sand (Table 3). This model best represents the F3 reservoir as estimated from the log data. Note that in this model, the tuning effect near the pinchout results in a nearly flat reflection event, changing the apparent dip to approximately 0.15 ms/trace (from 0.36 ms/trace). In the pinchout zone, the negative side lobe (indicated by an arrow in Figure 8) of the flat spot appears just above the reservoir top. Interpretation of stacked sections from such a geologic feature may be difficult to perform correctly because the polarity reversal is disguised as a flat, bright event.

The synthetic seismograms for the bright spot model are shown in the middle of Figure 8. In the bright spot model, the shale impedance is greater than that of the water sand and the gas sand (Table 3). This model shows negligible flattening due to tuning, and interpretation of such a structure is probably straightforward.

The results from dim spot modeling are remarkable, as shown in the bottom of Figure 8. In the dim spot model, the impedance of the shale is less than that of the gas sand and the water sand. Because dim spot amplitudes are low, the tuning effect at pinchout may not be noticeable. Going updip from the flank of the reservoir, the thin gas zone results in constructive interference between the positive main lobe of the dim spot (the reservoir top) and the positive main lobe of the flat spot (the GWC), and of their respective sidelobes, resulting in slightly enhanced reflections. Then, as the gas zone reaches one-fourth of the wavelength in thickness (the tuning thickness in a conventional wedge...
model), this constructive interference is reduced and destructive interference between sidelobes and mainlobes results in smaller amplitudes, reaching a minimum at one-fourth of the wavelength. As the thickness continues to increase to one-half of the wavelength, there is a slight constructive interference between the sidelobes of the two main reflections, resulting in a slightly enhanced negative reflection (the red line in Figure 8). It is possible that one’s eye, or an automatic tracking system seeking a bright spot, would continue to follow the negative sidelobe of the flat spot. The resulting seismic section shows a strong negative flat reflection over a strong positive flat reflection; this response is similar to that observed in F3 (Figure 1). These reflections exhibit a dip of flat to 0.03 ms/trace rather than the model dip of 0.36 ms/trace. This is not necessarily a result of tuning, but it is an effect of the low-amplitude dim spot itself.

We show that tuning effects can have significant effects on a true zero-offset seismic section, in which a flat spot terminates against a dipping interface. In the next section, we analyze and discuss amplitude versus offset and the importance of varied stacking angle ranges on the tuning effect.

Amplitude variation with offset and stacking up to and beyond critical offset

Amplitude variation with offset analysis

In contrast to the four conventional AVO classes, the negligible shear velocity contrast across any hydrocarbon-water contact makes its AVO response distinctive and unique. Specifically, the reflection coefficient for any flat spot is always positive and increases with offset, as is shown in Figure 4.

Figure 9 shows the AVO curves out to large angles for all four DHIs. To have confidence at large angles, it is necessary to solve the full Zoeppritz (1919) solution (we used code provided by the Consortium for Research in Elastic Wave Exploration Seismology [CREWES], which solves the equations as written by Aki and Richards, 1980). For reflections that occur at an interface at which the velocity increases, a critical angle will be encountered, beyond which the reflections undergo strong phase rotation. The flat spots and dim spots will always exhibit supercritical phase rotation (see the flat spot and dim spot curves in Figure 9b). Because the velocity increase across a flat spot can be significant, the critical angle may occur at surprisingly small angles, such as the 52° shown in our example. This may or may not be within the range of recorded data. Because postcritical reflections always undergo phase rotation, if stacking involves these postcritical reflections, the stacked output will exhibit large-amplitude nonzerophase wavelets. This effect may compound the similar wavelet distortion caused by tuning.

Figure 10 shows the result of convolving the AVO response in Figure 9 with a 50-Hz Ricker wavelet. This includes phase shifts for the flat spot and dim spot that extend beyond critical. The seismograms on the far-right in Figure 9 show the result of stacking these events over different angle ranges as indicated. As the stacking ranges increase, all hydrocarbon indicators other than the flat spot show an increase in brightness of the stacked trace without any change in wave shape. (The dim spot model does not include many traces beyond critical offset in the final stack.

Figure 9. (a) AVO responses for three different models (bright spot, polarity reversal, and dim spot) and flat spot (GWC) and (b) phase shift versus incident angle for flat spot and dim spot, the two that exhibit critical angles.

Figure 10. Synthetic CMP gathers exhibiting AVO responses for different models, using a 50-Hz Ricker wavelet. The figure at the right shows the wavelets generated by stacking the gathers over different angle ranges.
and the effect of its phase rotation is minimal.) The flat spot, on the other hand, shows not only an increase in amplitude but also a change in shape. For example, a zero-phase Ricker wavelet when stacked over 0°–70° approaches the appearance of a 90° wavelet. The earliest part of this is a “trough” easily misinterpreted as a negative reflection coefficient. Hence, flat spot events stacked beyond critical offset can generate spurious bright reflections that might be categorized as bright spots by the interpreters.

Muting based only on the NMO stretch may not remove the postcritical reflections and could mislead interpreters. Because muting is usually based on distortion caused by NMO, and not by angle, it is possible that some flat spots are stacked beyond critical angle.

Synthetic stacked seismograms in the wedge model

As we have seen, a zero-phase Ricker wavelet, when stacked over a range of 0°–70°, undergoes a significant phase rotation and might appear as a negative reflection event. Here, we investigate the effect of stacking over varying angle ranges within the wedge model.

To see the combined effect from tuning (due to a dipping interface encountering a flat GWC) and stacking with AVO and postcritical reflections, we ran the wedge model described earlier, but this time using wide-angle stacks rather than zero-offset reflections. Three different models (polarity reversal, bright spot, and dim spot) were prepared for 0°–30°, 0°–60°, and 0°–70° stacks, respectively, recalling that the critical angle for the flat spot in this model is 52°. The synthetic seismograms in Figure 11 show that the combined effect of tuning and supercritical stacking enhances the flatness of those spurious bright reflections. Table 4 summarizes the dip (in milliseconds/trace) of reflections affected by tuning effects and stacking ranges compared with the original geologic model dip, for these three different models.

The modeling results summarized in Table 4 show a significant decrease in interpreted dip angle for all models. This suggests that observed reflection events from the top of the reservoir can appear as a “flat” event, discordant with the structural trend because of tuning. The effect is quite striking if the top of the reservoir exhibits a polarity reversal or a dim spot over the gas zone.

Even the bright spot model shows that stacking beyond the critical angle can result in some apparently flatter events. The strong reflection from the reservoir top probably helps to avoid improper interpretation in most cases.

The maximum flattening effect was observed for the dim spot model. In this model, the top of the reservoir is nearly invisible, and this probably has the most significant implication for interpretation. These flat reflections in the case

Table 4. Summary of the dips (milliseconds/trace) from Figure 11, for the geologic structure and the negative reflections from three different models, stacked over different angle ranges.

<table>
<thead>
<tr>
<th>Dip/flatness (ms/trace)</th>
<th>Model types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geologic model (structural trend)</td>
<td>Polarity reversal</td>
</tr>
<tr>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Stacking range</td>
<td></td>
</tr>
<tr>
<td>Zero-offset (tuning effect only)</td>
<td>0.15</td>
</tr>
<tr>
<td>Stacking over 0°–30°</td>
<td>0.15</td>
</tr>
<tr>
<td>Stacking over 0°–60°</td>
<td>0.13</td>
</tr>
<tr>
<td>Stacking over 0°–70°</td>
<td>0.10</td>
</tr>
</tbody>
</table>
of a dim spot, marked with the red line in Figure 8, were caused by the tuning effect of the side lobes and are exaggerated when the nonzero-phase wavelet is stacked beyond the critical angle. Although the sonic log from a nearby well suggests that the reservoirs in the F3 block most likely exhibit polarity reversal, the dim spot model seems to best match the F3 seismic data.

For our particular data set, we know neither the muting criterion used in the original processing nor how much stretch was caused by NMO correction, so the previous discussion and analysis were restricted to stretch-free modeling. In the next section, NMO stretch and muting will be considered in our analysis.

**Normal moveout stretch and muting analysis**

**Subsurface model**

To estimate possible NMO stretch for different mutes, we extend our modeling to include the effects of NMO stretch on stacking.

To convert angles of incidence to offset distances, we created a true-depth model that is intended to resemble the area of block F3, based on the well-log data. This simple subsurface model used homogeneous flat layers extending from the surface to the base of the gas reservoir (Figure 12). We used the reservoir and shale parameters for the polarity-reversal case. In this model, we found the “critical offset” for the flat spot reflection (the surface offset distance to the critical angle of 52°) to be approximately 1300 m.

**Normal moveout stretch and muting analysis**

The “percent of changing frequency” criterion (Yilmaz, 1987), which qualifies the NMO stretching (frequency distortion in which events are shifted to lower frequencies) by the percent of changing frequency, is adopted here. A stretch limit of 50% changing frequency is taken to determine the muting zone and yields muting at 1100 m offset for the time of the flat spot reflection. This implies that postcritical reflections from the GWC (occurring at approximately 1300 m offset for our subsurface model) would have been automatically muted in our example. The details are provided in Figure 13, which shows the synthetic CMP gather before NMO correction and after NMO correction, with and without muting of events beyond critical offset.

In addition, the reflection hyperbolas’ intersection of the seafloor reflection with the flat spot reflection can be observed at approximately 1200 m. Because the maximum NMO stretch usually occurs when some of the reflection hyperbolas intersect one another (Buchholtz, 1972; Shatilo and Aminzadeh, 2000; Zhang et al., 2013), the traces around that offset are often muted; in our case, this offset happens to be close to the critical offset for the flat spot reflections. We conclude that the postcritical seismic data from flat spot reflections in F3 were most likely muted before stacking and excluded from the stacked output.

**Results and comparison with original seismic data**

Based on the analyses described above, reflections from GWC are likely to have been muted beyond the 1100-m offset, corresponding to an angle of incidence of 47°. Figure 14a shows the synthetic seismograms that result from stacking over an angle range of 0°–47° for the polarity-reversal case previously shown for different angle ranges. These perhaps best represent the example used from North Sea block F3. The synthetic seismograms demonstrate the flat, bright reflections caused by tuning and stacking. We think that this explains the observations in the actual stacked seismic data, as shown in Figure 14b.

**Results and discussion**

Bright reflections in block F3 of the Dutch North Sea were analyzed for possible sources of their flatness. Tuning and postcritical stacking were evaluated as possible reasons. For this purpose, zero-offset and wide-angle stacked sections were prepared by forward modeling. NMO stretch and muting were investigated to evaluate the possibility that stacking extended beyond the critical offset for our data set.

The tuning effect results showed a significant decrease in the reflection dip for the polarity-reversal and the dim spot cases. The polarity-reversal case is suggested for F3 based on well logs and the strength of the reflections, but the dim spot example also fits the data. In both cases, the synthetic seismograms show that the reflections appear to become very flat for thicknesses under one fourth of the wavelength. For the dim

![Figure 12. An assumed subsurface model of F3 block (homogeneous flat layers) and estimated rock properties used to generate CMP gathers for stacking. A, B, C, and D represent the reflecting interfaces identified in Figure 13a.](https://pubs.geoscienceworld.org/interpretation/article-pdf/3/3/SS37/3015102/INT-2014-0210.pdf)
spot case, the modeling results are particularly striking because the dim spot event is of very low amplitude and the bed boundary could be misidentified from the (enhanced) sidelobe above the GWC. The result for the dim spot is a strong negative flat reflection over a strong positive flat-spot reflection; this response is similar to that observed in F3. If an interpreter or tracking system is seeking a bright spot, they might think that they have found it in these large negative amplitudes.

If postcritical events were included in the stacking output for our data set, additional distortion to the event could have resulted. Flat spot events stacked beyond critical offset can generate spurious bright reflections that might be categorized as bright spots. The two phenomena (tuning effect and supercritical stacking) could act together, strongly modifying the final results in an actual reservoir. This effect is even more striking if the top of the reservoir exhibits a polarity reversal over the gas zone. For our particular data set, the stretching and muting are unknown, but our simple models suggest that postcritical seismic data were excluded in the stacking output.

Based on these analyses, we conclude that the tuning effects and postcritical stacking can make bright reflections in F3 flatter and brighter. Postcritical stacking likely did not occur, and the tuning effect is presumed to be the main source of the bright, flat events in the F3 data. The tuning effects can be significant for both dim spots or polarity reversals, making these reflections ap-

**Figure 13.** (a) Synthetic CMP gather associated with subsurface model of Figure 12 before NMO correction; notice the intersections of reflection hyperbola from the water bottom A, with reflections from target horizons B, C, and D at far offsets (approximately 1200 m). (b) The same CMP gather after conventional NMO correction without muting; notice the distortion of wavelets caused by the NMO stretch, especially for shallow and far-offset reflections. (c) The same CMP gather after NMO correction and muting; notice that seismic data beyond the critical offset (1300 m) for the flat spot reflections have been muted.

**Figure 14.** (a) Stacked synthetic seismic section generated by stacking the polarity-reversal model over $0^\circ$–$47^\circ$ and (b) actual stacked seismic data from North Sea block F3. Blue lines indicate a dip of the geologic model (in Figure 14a) and the true structural trend (in Figure 14b, based on a phantom horizon); red lines indicate the flatness of the respective bright negative reflections.
pear as bright spots. Care should always be taken when interpreting stacked data, with the recognition that it is not the same as zero-offset data.

Conclusion

The stacking of flat spot reflections beyond the critical angle can boost their amplitudes significantly while accompanied by a significant phase shift in the stacked output. Tuning effects can also change the amplitudes and apparent polarity and phase in the cases we examine. Individually, these effects can result in fairly flat, bright negative events overlying strong positive reflections. The effect can be strong enough that it can even make a dim spot appear as a (flat) bright spot.

Postcritical seismic data of flat reflections were most likely excluded from the stacked output of our data set, based on our NMO stretch and muting analysis. We conclude that the tuning effect is the key reason for the flatness of the bright reflections at shallow depths in block F3 of the Dutch North Sea. We further conclude that these bright reflections are not typical bright spots but appear as such because of the tuning effect.

In addition, although for our particular data set, postcritical offset data were probably muted based on traditional criteria, we recommend that care should be taken while dealing with reflection data containing a wide range of incidence angles, where those criteria may not be routinely applied (e.g., crosswell-seismic data). Muting applied solely on the basis of NMO stretch might include postcritical reflections, and the stacked output will be significantly altered.

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References


Gassmann, F., 1951, Uber die elastizität poroser medien (Elasticity of porous media): Vierteljahrschrift Der Naturforschenden Gesellschaft in Zurich, 96, 1–21.


Hilterman, F. J., 2001, Seismic amplitude interpretation: Distinguished Instructor Short Course, SEG/EAGE.


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