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TUNING, INTERFERENCE AND FALSE SHALLOW GAS SIGNATURES IN GEOHAZARD INTERPRETATIONS: BEYOND THE ‘λ/4’ RULE

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ABSTRACT

Shallow gas presents a significant geohazard for drilling operations, with implications for costly well deviations and inherent blow-out risks. The archetypal seismic signature of shallow gas – a 'bright spot' – can be falsely induced by tuning, whereby reflections from closely-separated horizons stack and constructively interfere. According to established guidelines, maximum constructive interference is typically expected where horizons are separated by one-quarter wavelength (λ/4) of the seismic wavelet. Here, we test the circumstances in which false gas signatures can be induced from tuning, and the conditions in which the 'λ/4' guidelines for interference become problematic. We simulate normal-incidence seismic data for a variety of reflectivity models, incorporating different contrasts in reflectivity magnitude and polarity. We simulate acoustic impedance by supplying initial geological parameters to Gassmann's rock physics equations, allowing bulk density and compressional (P-) wave velocity to vary between ~1200-2100 kg/m^3 and ~1460-1670 m/s, respectively for non-gassy sediments and 1160 kg/m^3 and 170-200 m/s for gassy sediments. Tuning is considered for a Ricker wavelet source pulse, having both peak frequency and effective bandwidth of 60 Hz. Tuning effects are able to mask a gas pocket, corresponding to a 'false negative' signature which represents a significant hazard for drilling operations. Furthermore, the widely adopted 'λ/4' assumption for constructive interference is not always valid, as the brightest seismic responses can appear for thicker (<'λ/2') and thinner (>'λ/16') beds, depending upon the stratigraphy. Similar observations are made both qualitatively and quantitatively for real seismic responses, in which reflections from a series of dipping clinoforms interfere with those from an overlying unconformity. We conclude that greater attention should be paid to the interpretation of shallow gas risk; specifically, the

effect of reflector geometries should not be overlooked as a means of producing or masking seismic amplitudes that could be indicative of a hazardous gas accumulation.

INTRODUCTION

Gas is widely distributed as a pore fluid in the shallow sediment layers of most of the world's basins. In hydrocarbon exploration, the presence of shallow gas can be a useful indicator of deeper economic reserve of gas, or it can be present as a significant gas reservoir in its own right (e.g. the Peon gas field in the North Sea). For most purposes, however, it is considered as an engineering hazard, and presents a significant risk in hydrocarbon production and sea-bed engineering. Blow-outs from drilling into a pressurised gas pocket are of particular concern, and the West Vanguard blowout that occurred at 523m RKB on the Halten Bank, Norwegian Sea serves as a prime example of the tragic consequences (human, economic and environmental) that can arise from such an event (Nørstebø et al., 1986; Grinrod, Haaland & Ellingsen, 1988).

The risk posed by shallow gas can be mitigated by undertaking a risk assessment prior to the commencement of drilling operations, whereby the analysis of shallow seismic data is a key component. In such data, shallow accumulations of gas are often clearly visible as a high-amplitude anomaly (Judd and Hovland, 1992). Gas-charged sediment typically has a high acoustic impedance contrast with overlying and underlying strata, since seismic velocity is significantly reduced in the presence of small gas concentrations (Gardner, 1988), whilst the bulk density is much less affected. The undrained strength of sediment is reduced by 25% with a total gas volume of only 1-2% (Thomas, 1987; Sham, 1989).

Mapping the location of shallow amplitude anomalies is an effective means of constructing a risk map, to mitigate against disastrous blow-outs. However, a significant fraction of anomalies may present as ‘false positives’ or ‘false negatives’. In the former case, seismic amplitudes may exceed some critical threshold for a gas anomaly, but no gas is encountered upon drilling. The consequence is that optimal drilling strategies are unnecessarily ruled out. Less common, although more hazardous, are false negative gas signatures - where no evidence of gas is perceived in the seismic record but a gas accumulation is observed upon drilling. With no warning from the seismic hazard map, a hidden anomaly of this kind could be disastrous. A comprehensive seismic hazard map, therefore, not only delineates the extent of amplitude anomalies, but also incorporates the potential origins of the amplitude anomaly. False gas signatures, whether positive or negative, can arise because of tuning effects that are caused by interference between reflected wavelets. Understanding the origins of such responses is the key focus of this paper.

Tuning phenomena are commonplace in the shallow section of seismic data, particularly in the previously glaciated regions of the North Sea and Norwegian Sea, since the glacial deposits are often dominated by thin sediment beds, with inherently closely-spaced horizons (Van der Meer, Menzies and Rose, 2003). Wavelet interference is therefore widespread although seldom predictable; constructive interference causes an anomalously high amplitude response that resembles shallow gas, whereas destructive interference may mask a genuine gas response. Similar interpretative dilemmas are, of course, encountered in seismic reservoir characterisation, but the availability of borehole logs removes much of the ambiguity from the analysis of the seismic response. However, such datasets are seldom available for the shallow marine case, and the extent to which the risk of false signature misinterpretation of shallow gas are appreciated in the geotechnical industry is unclear.

To generalise tuning effects, a 'rule-of-thumb' has arisen that implies that maximum constructive interference occurs where horizons are separated by ¼ of the incident wavelength (λ/4). This generalisation follows from the seminal work of Widess (1973), who model-tested the tuning response of a single thin bed surrounded by homogenous sediment (using two equal but opposite-polarity reflection coefficients as top and basal reflection interfaces). The study established the limit of vertical resolution as λ/8 in noise-free data, but λ/4 as a realistic threshold – a conclusion that has since been widely reported (Ashcroft, 2011; Avseth, Mukerji, and Mavko, 2005; Chopra and Marfurt, 2007; Li et al., 2015) regardless of the match between the genuine subsurface reflectivity and the simplified Widess (1973) model.

Modest variations to this simple ground model can yield significant deviations from the 'λ/4 rule'. Chung and Lawton (1990) considered the resolution of reflectivity models that had unequal, yet opposite-polarity reflection coefficients. They showed that the maximum amplitude of the composite waveform resulting from the two interfaces increases linearly with layer thickness for equal and opposite reflection coefficients up to λ/4, but that there is a non-linear relationship between thickness and amplitude for unequal reflection coefficients. Additional to the underlying reflectivity, wavelet shape also plays a complicating role in resolution and interference. The observations of Widess (1973) were defined for a zero-phase wavelet. Lee et al. (2009) developed this by considering both the resolution characteristics of not only zero-phase, but also minimum-phase Ormsby wavelets. They concluded that the nominal tuning thickness can be less than λ/4 in both cases. While minimum-phase wavelets would unlikely to be used in shallow hazard assessment, the scope for deviation from the λ/4 assumption is noteworthy.

In this paper, we conduct an investigation of the circumstances in which seismic amplitude anomalies may specifically be falsely interpreted in terms of the presence or absence of shallow gas accumulations. We show situations arising from reasonable variations in stratigraphy alone which, when treated simply with the 'λ/4 rule', would be vulnerable to misinterpretation. We conduct tests to assess the variability of tuning responses with varying geological sequences, using a synthetic seismic model and real data from the Norwegian Sea, and show that each ground model has a unique tuning response. In addition, we show that in cases where gas is present in the stratigraphy, there is the potential to mask the amplitude anomaly from the destructive effects of tuning.

METHODS

Synthetic Modelling

Tuning effects were studied using 1D models of normal-incidence seismic reflection data. These models are derived by supplying representative values of sediment and fluid properties into Gassman's equations (1951), a set of relationships used to derive the compressional (P-) wave velocity (and bulk density) from fluid and matrix components. Modelled quantities are validated against literature values (Anderson and Hampton, 1980) of bulk modulus, bulk density and P-wave velocity. The capacity of a model to produce a 'gas-like' anomaly is validated against seismic data from the Peon gas field, North Sea. On defining bulk density and P-wave velocity, models are converted to acoustic impedance and, thereafter, to reflection coefficient. Representative seismic traces are then produced by convolving the reflectivity series with a Ricker wavelet; the convolutional model incorporates reflection and transmission losses across each interface, but neither noise nor the effects of noise-suppression algorithms are considered. The following sections describe the detail of our simulation approach.

Model inputs

Gassmann's equations (1951) use simple mixing models for sediment components to derive a compressional velocity and bulk density of each sediment layer. The use of Gassmann's equations to calculate the effect of saturating fluids on the compressional velocity in unconsolidated sediments is supported by Gardner, Gardner and Gregory (1974). It is assumed that each layer is composed of three principal components: the frame (dry framework drained of pore fluid), matrix (grains) and pore space constituents. These components are characterised by individual properties of density, velocity, water saturation and elastic moduli, here assigned using values established in previous studies (Table 1; Stoll and Bryan, 1970; Stoll, 2001; Al-Khateb, 2013). The equations assume that i) the sediment is homogeneous, elastic and isotropic, ii) the porosity is constant and in pressure equilibrium, iii) there is no movement of pore fluid across boundaries, and iv) there are no chemical reactions between the fluids and the grains, i.e. shear modulus is constant (Al-Khateb, 2013).

Since we simulate normal incidence reflections, only the P-wave velocity, v_P, is derived as:

$$v_p = \sqrt{\frac{K+\frac{4}{3}+\mu}{\rho_B}} \quad (1)$$

where K is sediment bulk modulus (Pa), μ is shear modulus (Pa) and ρ_B is bulk density (kg/m^3). Compressional velocities between ~1460-1670 m/s and bulk densities of ~1200-2100 kg/m^3 are calculated for sediments with varying proportions of clay and sand.

Bulk density is a composite of grain density (ρ_g), pore fluid density (ρ_{fl}) and the porosity (ϕ) of the sediment (using the proportional average of the sand and clay fractions), given by:

$$\rho_B = \rho_g(1-\varphi) + \rho_{fl}\varphi. \quad (2)$$

Fluid density is given by:

$$\rho_{fl} = S_w \rho_w + (1 - S_w)\rho_{hc} \quad (3)$$

where Sw is fractional water saturation, and ρ_w and ρ_{hc} are densities of the water and hydrocarbon (here, gas) fractions respectively. A value of Sw = 0.7 implies that 70% of pore space is occupied by water, the remainder by gas.

We fix porosity at 0.34 and 0.61 for unconsolidated sand and clay respectively (following Terzhagi and Peck, 1967). Void ratio (e) is established in order to calculate porosity (ϕ) using:

$$e = \frac{G_s \rho_w - \rho_{sat}}{\rho_{sat} - \rho_w} \quad (4)$$

$$\phi = \frac{e}{1+e} \times 100 \quad (5)$$

where G_s is specific gravity and ρ_{sat} is the saturated bulk density (kg/m^3).

For small additions of gas, v_P drops significantly (Anderson and Hampton, 1980), due mostly to the effect of gas on the bulk compressibility of the sediment volume. Velocity values of ~170-200 m/s are calculated with the addition of gas, consistent with Anderson and Hampton (1980) for gas saturations greater than 1%, and Konstanaki et al. (2016) and Angioni et al. (2013) at shallow onshore sites. Of course, higher velocities than this are plausible, attributable (Wilkens and Richardson, 1998) to local velocity averaging in gassy and non-gassy sediment, and/or a prevalence of smaller-sized bubbles in the total gas volume. However, by including the slower velocities, our models simulate the strongest likely reflectivity – the motivation being that if the potential exists for geometric effects to mask strong reflectivity, it also exists for weaker contrasts.

A fundamental concept in Gassmann's equation is that the bulk modulus is affected by fluid substitution, but the shear modulus is not. The gas presence will inherently reduce sediment density too (to ~1160 kg/m^3 in sand) but a reduced density, of itself, would increase the velocity (Equation 1); it is the effect on bulk modulus reduction that is the main cause of the velocity drop (Lee, 2004).

Densities and velocities are combined to define acoustic impedance (Z, = $\rho_B v_P$), and a reflection coefficient series. The normal incidence reflectivity, R, of each interface is

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (6)$$

where subscripts 1 and 2 respectively denote material properties above and below the interface. The reflectivity series is convolved with a broadband Ricker wavelet (Figure 1) of 60 Hz peak frequency, with effective bandwidth (i.e., bandwidth measured at the 50% amplitude threshold) spanning 30-95 Hz. This frequency conforms with the recommendation of Bulat & Long (2006), who suggest 60 Hz as the lowest frequency that would make exploration data suitable for site investigation purposes. While they also concede 60 Hz is somewhat high for typical exploration data, our study highlights the range of tuning responses that could be anticipated if the guidance of Bulat & Long (2006) was followed.

Transmission loss and amplitude gain

At each interface, a certain proportion of wavelet amplitude energy is reflected back to the surface, implying that a reduced fraction is transmitted. The available wavelet amplitude therefore decreases with depth, irrespective of interference effects. Such transmission losses are included in the model, but loss due to scattering and/or absorption is omitted (their effects are in any case negligible for the short intervals we consider). Other authors neglect interface transmissivity (e.g. Lee, Lee and Kim, 2009; Chung & Lawton, 1995), but we consider it sufficiently important to include because it will materially affect the results of a study such as this, in which closely spaced reflector responses are interfering with each other.

RESULTS

Synthetic Results

Tuning with horizon couplets

Twelve different reflectivity models with two successive horizons of varying polarities and magnitudes, were simulated to test tuning responses (Figure 2). The layer thickness is reduced in each test from 1λ to λ/24 and the leading trough amplitude (maximum negative amplitude) is measured. This attribute is used since strong negative amplitudes would often be considered to be the least ambiguous diagnostic of a shallow gas accumulation. While it should be noted that not all of our layer configurations are able to trap gas (i.e., a potential physical seal is absent), these hypothetical layer configurations are simply synthetic models to show the range of tuning characteristics that they could produce.

Figure 3 shows the maximum negative amplitude attribute for the all reflectivity models considered. Reflectivity models that exhibit a large amplitude change are of interest as these could represent constructive or destructive interference of a potential gas signature. Note that tuning responses for beds thinner than λ/8 are not resolved in real data, therefore Figure 3 emphasises thicknesses in the range of λ/2 and λ/8. Test 4 represents a validation model since its equal-and-opposite reflectivity conforms with the configuration defined by Widess (1973). For this case, the 'λ/4' characteristic is evidently valid; however, it is immediately obvious that the 'λ/4' does not describe tuning for other cases, thereby highlighting the need for cautious interpretation. Maximum constructive interference occurs at λ/4 for six of the twelve tests (4, 5, 6, 7, 8 and 12) and, of these, only three construct by greater than 20% (Tests 4, 5 and 12). Test 4 is an 'equal and opposite' scenario with a positive reflection preceding the negative reflection and Test 12 is the opposite. Test 5 is a small negative reflection coefficient followed by a large positive reflection coefficient. In these examples, the λ/4 rule may be valid. Otherwise, the remaining tests reveal maximum constructive interference at bed thickness other than λ/4. Tests 1, 2 and 3 comprise positive reflection coefficient combinations and reveal maximum constructive interference at λ/2. The remaining reflection coefficient patterns (9, 10 and 11) reveal maximum constructive interference at bed thicknesses < λ/8, unlikely to be resolved in real seismic data (Widess, 1973).

Amplitude destruction is encountered at λ/4 in Tests 9, 10 and 11 of 49%, 15% and 7%, respectively. Test 9 consists of two equal negative reflection coefficients and reveals maximum destructive interference at λ/4 when the negative peak of the first reflection is suppressed by the leading positive trough of the second. In this scenario, if there is no gas in the ground model and the negative reflection coefficients represent a simple transition into sediments of lower acoustic impedance (e.g. sand to silt, clay), false positive gas signatures are induced at bed thicknesses of λ/8 and thinner. If the negative reflection coefficients are a result of gas, the gas response is visible at λ/8 (but likely to be below seismic resolution) and where we would expect it according to the λ/4 rule of thumb, the gas signature becomes hidden. This could lead to a false negative interpretation of shallow gas.

Tuning with multiple thin beds

The more likely scenario for a real case is that the observed reflectivity is the result of interference across several closely-separated horizons. When a ground model of alternating sand and clay layers of the same thickness is tested, maximum constructive interference indeed occurs at λ/4 and a false positive gas signature is induced. A typical example of beds thinning in this manner is the pinch-out of sediment infill onto the margin of a channel or of a syn-rift depositional wedge. However, when gas was introduced into the third layer (sand) of the same model, the interference pattern is very different (Figure 4). The 'gassy' signature is of a similar amplitude to the seabed reflection. The leading trough of the gas trace constructs at a bed thickness of λ/2 by 38%. Crucially, at bed thickness of λ/4, the gas signature is hidden (destructed by 233%) and a false negative gas signature is induced. For a 60 Hz wavelet and a velocity of 2000 m/s, λ/4 implies that 10 m thick layers are vulnerable to this effect. For the higher frequencies (e.g., 120 Hz; Atkins, 2004) typical of dedicated site-survey data, λ/4 may be closer to 4 m, hence gassy beds of this thickness are vulnerable to being hidden.

It is also worth noting that variations in gas saturation above 3% cause relatively little change in v_P (Domenico, 1977; Murphy, 1984; Lee, 2004). As such, tuning effects can mask a layer even with very high gas saturation.

DISCUSSION

Gas signatures in real data

Figures 5 and 6 highlight interference effects in real data, from 3D seismic data from the Norwegian continental shelf. The Naust Formation is a Late Pliocene (3.60-2.58 Ma) unit, in which the high amplitude Upper Regional Unconformity (URU) truncates a series of clinoform wedges. A clinoform is a depositional surface expressed in seismic with a sloping morphology (Mitchum et al., 1977). The URU truncates the clinoforms such that only the foresets are apparent and it separates them from flat-lying till units above. Unfortunately, there are no wells that penetrate these particular clinoforms, but local wells penetrating through others within the Naust Formation reveal sand with hemipelagic mud between. Different interference patterns are anticipated between the URU and the underlying clinoforms, given the change in the vertical separation of reflectivity as the clinoforms converge on the URU. Figure 5 shows a seismic cross-section through a series of clinoforms, extracted along the profile included in Figure 6. Figure 6 itself is a plan-view image of URU reflectivity, shown as a combined variance (i.e. trace-to-trace variability over a given sample interval) and minimum amplitude map.

The amplitudes in Figure 6 show a characteristic tuning response, in which the maximum negative amplitude brightens (yellow) and then dims (grey) towards the truncation of a clinoform. It is evident that each clinoform truncation expresses this response in a unique manner, with some producing brighter amplitudes over a larger distance than others. For example, the approach of clinoforms 4 and 5 (upper row of Figure 5) to the truncation are not as bright as those of clinoforms 6 and 7 (lower row of Figure 5), i.e. the degree of constructive interference is reduced. Since this dataset is acquired and processed to maintain a consistent waveform, and each clinoform converges on the URU at a similar angle, the differing tuning responses can be attributed only to the different lithology of each specific clinoform.

The relationships we simulated in our synthetic analysis, where only lithology was varied, are therefore likely to be appropriate for this real dataset. Furthermore, it is possible that the quantitative relationships we observed between amplitude and layer thickness could be replicated for this real data setting. Figure 7 shows the detail of clinoform 7 (lower row, Figure 5), showing the seismic profile as wiggle traces, with 'red-blue-red' (trough-peak-trough) polarity giving a 'hard' response (i.e., the response generated at an interface across which there is an increase in acoustic impedance, such as clay to sand). Both the URU and the clinoform exhibit hard responses and hence show positive reflection coefficients that are similar in magnitude. Our modelling suggests that this combination of reflectivity experiences maximum constructive interference at λ/2, which is consistent with the results observed in synthetic Test 1 (Figure 3). The bed thickness (time between peaks) and amplitude curve (of the leading trough of the clinoform reflection) are presented above the seismic cross-section. Bed thickness decreases from left to right and maximum constructive interference occurs when the bed thickness is 20 ms. Here, wavelet period is a suitable proxy for wavelength as we do not expect large lateral contrasts in velocity. We measure wavelet period at 35 ms (28 Hz dominant frequency) hence it appears that maximum constructive interference occurs at approximately λ/2 (i.e., one half-period). In addition, models suggested amplitude boosting of 70%, comparable to the observed increase of 73%.

Current industrial practice

While the effects of interference may be familiar with regards to their potential for producing false-positive gas anomalies, there is less recognition that interference can obscure a genuine gas signature. We have shown a range of geological models for which this is possible.

The hydrocarbon industry uses a rigorous procedure for shallow gas assessment in order to avoid gas in drilling activity, using both quantitative (seismic amplitude) and qualitative (contextual geological and previous experience) evidence. Commonly, a risk matrix will be used that incorporates amplitude and the type of evidence (i.e. bright spot, turbidity, blanking, in some cases AVO class), although such matrices vary between companies. Furthermore, the nature of the assessment is subtle and a whole variety of evidence accompanies each anomaly, hence the classification is very subjective: effective communication is required to integrate the opinions of the contractor, consultant and operator.

AVO (amplitude vs. offset) analysis has been considered to aid this assessment, combining acoustic impedance with the shear wave velocity of sediments. As such, a richer set of quantities (e.g. Poisson's ratio) can be obtained to describe sea bed sediments. The added value can be used to distinguish, for example, a shallow gas accumulation from a shallow coal layer; both of these would give strongly negative reflections in normal-incidence seismic data, but would be distinct in AVO given the different shear wave velocities and resulting Poisson's ratios (Thore and Spindler, 2013).

However, AVO analysis is vulnerable to poor data quality and normal seismic processing (i.e., that priorities imaging over amplitude preservation) can introduce further false signatures (Paternoster and Des Vallières, 2008). In its usual application in reservoir analysis, AVO requires multi-channel seismic data and offsets that are sufficiently large to give incident angles up to 30 degrees. For a typical geotechnical survey of an offshore target, the usual procedure is to acquire single-channel data for geology less than 100 m below the seabed, therefore multi-channel requirement for AVO characterisation is moot (IOGP, 2015). In any case, even where multi-channel data are available, industry tests have shown that any AVO anomaly from a typical geohazard is also present in full-stack amplitudes and as such, often is not pursued as a useful method for characterizing gas hazards. Hence, normal-incidence seismic amplitude and phase are still the main means of detecting shallow gas and the problem of false positive and negative responses then remains an ambiguity that relies heavily on experience and geological knowledge to ameliorate. As such, we emphasise caution in interpretations where tuning is likely to be present and suggest consideration of tuning scenarios beyond the '$\lambda/4$ rule', whereby maximum constructive interference could occur at alternative bed thicknesses. Where data are available, we suggest that AVO should be considered to aid shallow gas assessment, particularly in regard to false positive interpretations.

CONCLUSIONS

We demonstrate that wavelet interference and its tuning response is highly dependent on the inherent geology and hence the nature of the reflection coefficients, as well as bed thickness and wavelet shape. Although widespread, we emphasise that the '$\lambda/4$-rule' should be applied cautiously, as constructive interference can peak at thicker ($\lambda/2$) and thinner ($<\lambda/8$) bed separations. Real examples of tuning at clinoform truncations in the

Norwegian Sea support the lithological influence on tuning response. Significantly, the tuning response has the capacity to hide gas as well as induce a gas-like signature, hence careful consideration of thin beds and the tuning response during seismic interpretation is suggested, which could include the support of AVO analysis.

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TABLES

Table 1: Geological properties used in modeling, and their sources in the literature.

Property	Value	Citation
Bulk modulus of frame (K^*)	26.3 GPa	Stoll (2001)
Bulk modulus of clay (K_{clay})	14.9 GPa	Al-Khateb (2013)
Bulk modulus of sand (K_{qtz})	36.0 GPa	Stoll (2001)
Bulk modulus of water (K_w)	2.27 GPa	Stoll (2001)
Density of sand (ρ_{sand})	2650 kg/m^3	Stoll (2001); Stoll and Bryan (1970)
Density of clay (ρ_{clay})	2300 kg/m^3	Stoll (2001); Stoll and Bryan (1970)
Density of water (ρ_w)	1026 kg/m^3	Stoll (2001)

FIGURE CAPTIONS

Figure 1. Source pulse utilised in model. Top: frequency spectrum with peak frequency at 60Hz. Bottom: amplitude form with time.

Figure 2. Reflection coefficient couplet tests. Test number, description, example ground model and schematic representation is included.

Figure 3. Tuning response as a percentage change of trough amplitude as bed thickness is reduced, according to descriptions in Figure 2. Bed thicknesses thinner than $\lambda/8$ are faded as these would be below seismic resolution.

Figure 4. Synthetic wedge model. A gas signature is masked as a result of tuning, giving a false-negative seismic response.

Figure 5. Seismic profile to show clinoform truncations against URU. White boxes correspond to clinoform truncations indicated on the map in Figure 5. Profile is split into two rows for clarity.

Figure 6. Minimum amplitude map (with variance) of URU to show subcropping clinoform truncations and corresponding seismic profile (indicated by yellow line). White boxes on the map correspond to clinoform truncations indicated on the seismic

profile in Figure 4. The figure clearly reveals the typical tuning response of 'brightening (yellow) –dimming (grey)' as each clinoform horizon tunes with URU horizon above. Since the wavelet shape is uniform throughout and thickness changes similarly for each clinoform, tuning differences at each truncation are attributed to lithology. This highlights the sensitivity of tuning to specific geological sequences.

Figure 7. Tuning in real data. A: seismic profile revealing two clinoform truncations against URU ('6' and '7' from Figures 5 and 6). Black box indicates tuning truncation of interest ('7') that is enlarged in 'B'. B: Clinoform truncation with wiggle traces (enlarged); the effect of interference on amplitude is clearly visible. A schematic representation of the reflection coefficients of the tuning horizons is presented in red. Graph above shows percentage change of trough amplitude (blue) and bed thickness (orange). Guidelines are provided to indicate the positions of 1T, T/2 and T/4 on the seismic profile, where T is the time period for one wavelength. Maximum amplitude constructive interference of 73% occurs at ~T/2; consistent with our model results.