Introduction

Chalk is largely assumed to be an uninteresting, homogeneous mass rarely garnering much interest in the geoscientific community. The following aims to reinvigorate interest in this neglected rock type with examples from two vintage seismic reflection surveys from the United Kingdom Continental Shelf (UKCS), reprocessed this year using the latest broadband and 3D pre-stack full-waveform inversion (FWI) processing workflows. Although there exists local variation, these two studies will focus on the Upper Cretaceous North Sea Chalk Group, which extends across the entire UKCS (Figure 1).

The first study, “West Wick 2019”, is situated in the Moray Firth Basin. The basin, situated between the East Shetland Platform and Central North Sea, was submerged in the Cretaceous by the incursion of the Boreal Ocean that led to the deposition of a thick sequence of chalk and chalk marl laterally correlatable with the chalk in the Southern North Sea (Andrews et al. (1990)). Although originally thought to be a homogeneous mass, a novel application of FWI revealed the 500-m thick sequence of chalk to contain a high degree of complexity in the velocity model confirmed independently by sonic logs. Using this enhanced model, we reveal refined imaging sub-chalk and the implications on hydrocarbon risk reduction.

Moving southeast, the second study, “Cavendish 2019”, is situated at the northern edge of the Southern North Sea Basin. Building on previous experience with chalk in shallow water, coupled with local marine charts and biota studies, we show how an enhanced velocity model can give us clues about the poorly imaged shallow seabed. Finally, during preliminary model building, we rediscover the Silverpit Crater, a surprisingly well-preserved asteroid impact in the top chalk.

West Wick 2019

The West Wick 2019 project was acquired using a 3.6-km conventional streamer in 1998. Straddling Quads 12 and 13, the survey sits centrally in the Moray Firth Basin. Encompassing the West Wick field Dee, Nutmeg, and Surprise discoveries, this is an area of high potential prospectivity at multiple stratigraphic levels. Despite numerous leads, many structures have been left undrilled due to uncertainties of breeched fault seals after partial inversion and erosion in the Tertiary, which could not be resolved by the original 90s data.

Multiple reservoir intervals are targeted in the area from the post-rift Lower Cretaceous (Captain, Coracle, and Punt sands), syn-rift Upper Jurassic (Alness Spiculite, Ross, Ettrick, Buzzard, and Volgian Burns sands), Lower Jurassic (Beatrice) and, finally, the pre-rift Permian (Rotliegend) and Devonian.
Seal lithologies appear widespread, particularly the Upper Cretaceous (Cromer Knoll claystones and shales) with thin intra-shales between thick sand sequences and Upper Jurassic (Heather Shales and Kimmeridge Clay). Structural traps of 2-way or 3-way dip closures exist with faults forming the rest of the structure for both the Lower Cretaceous and deeper reservoirs. Stratigraphic traps exist where Lower Cretaceous and Upper Jurassic sand bodies such as the Punt sandstone pinch-out. Previous processing efforts uncovered that the key to imaging these thin prospective sands and fault seals was a tight control on Tertiary shallow channels and, most importantly, the velocity variation related to the chalk.

A novel approach was applied to model the velocities within the Tertiary and chalk layers. The first band of FWI attempted to model the initial bulk velocity within Tertiary. Fifteen iterations were applied to resolve velocity heterogeneity between shallow channels and the overburden, utilising the maximum frequency of 10 Hz. This was followed by 12 iterations forming the second band, targeting maximum frequencies of 12 Hz to further enhance the overburden resolution and model the variable velocities within chalk. Four iterations of global reflection tomography were performed after FWI to update the velocities in the deeper Jurassic and Devonian, as well as refining shallow velocities, achieving focussed imaging of slow shallow channels above (Figure 2), and sand stringers within the chalk (Figure 3).

Chalk is known by its strong acoustic impedance, generating different types of multiples. Having both water bottom and chalk present in the shallow added uncertainties to deeper prospects’ interpretation because of residual strong multiples observed while studying vintage data. Also, noise content and frequency limitations caused issues in the past. Therefore, the contemporary broadband workflow implemented focused on attenuation of ghost effects and multiple contaminations. Adaptive deghosting (Rickett et al., 2014) was used to eliminate the source and receiver ghosts, allowing the broadening of the frequency content from shallow to deep. Short-period surface-related multiples were modelled using a combination of 3D model-based water-layer demultiple and true-azimuth 3D surface-related multiple elimination (SRME), while long-period surface-related multiples were modelled using 3D SRME only. Short- and long-period multiples were adaptively subtracted, frequency-dependently, utilising a cascaded approach from the raw data. This was followed by interbed multiple attenuation using seabed and top-chalk horizons as multiple generators. The reprocessed data were migrated after regularising and interpolating the processed traces using 4D anti-aliased interpolation, improving the signal-to-noise ratio and effectively constructing primary diffractions.

Interpretation of the new data shows the chalk slumping off the West Bank High south of the survey area. In the north, re-sedimentation and weathering were observed in the top chalk overlain uncomfortably by the Maureen formation, creating a fast layer of complex sand lenses, as suggested by

Figure 2 Reprocessed data from the West Wick 2019 survey in the Moray Firth Basin. A 150-m depth slice overlain by the interval velocity cube showing slow (1500 ms\(^{-1}\)) shallow channels in the faster (1800 - 2100 ms\(^{-1}\)) surrounding sediments, a key complexity in the Moray Firth Basin.
Kilhams et al. (2014). An increase in velocity is also observed within the chalk, thought to be attributed to the relationship between the Red Chalk and two parallel sand stringers highlighted using the sweetness attribute as suggested by Andrews et al. (1990). Below, the base chalk is clearly resolved and the continuity of the Punt and Coracle marginally enhanced, highlighting improved amplitude fidelity and thin-bed resolution, reducing correlation uncertainty. The footwall of the Smith Bank Fault is clearly imaged, including strata below. Finally, pre-rift strata on the hanging wall appears simplified, with a sharper broadband wavelet and reduced interbed multiples de-risking the Upper Jurassic play and possibly the Permian play by revealing the elusive Devonian source.

Figure 3 Data from the reprocessed West Wick 2019 survey in the Moray Firth Basin. Inline with interval velocity overlay (main) showing velocity inversion caused by chalk (red arrow) and the intra-chalk variation (red). Bottom-left: Zoom of seismic section showing rugose nature of top chalk (black arrow) and delineation of base chalk (white arrow). Bottom-right: Sweetness attribute highlighting two postulated sand stringers (red arrows) between top and base chalk.

Cavendish 2019 survey

Broadband pre-stack depth migration reprocessing of the 2019 Cavendish survey including two adjacent and publicly-available surveys created a total contiguous area of 2,723 km². It was clear from interpretation and client feedback that understanding of the chalk was vital for the velocity model. When mapped, it was seen that the chalk sub-cropped the seabed, but, due to the shallow water, the wavelet lacked the resolution to show whether the chalk was overlain by sediments or exposed to the North Sea waters, and how much contemporary submarine erosion had occurred exposing the deeper, compacted chalk.

Analysing the first iterations of FWI suggested increased slowness compared to the initial model. It was hypothesised that sub-glacial channels had incised part of the chalk, depositing anomalously slow sediments and leaving ridges of disintegrated chalk. Admiralty charts indicated chalk at seabed and marine biota surveys in the last decade discovered the largest chalk reef system in the world in this region of the Southern North Sea, which reinforced this hypothesis. During preliminary interpretation for the velocity model, an interesting anomaly was rediscovered southeast of the study area.

In August 2002, Nature Magazine published a letter from geologists Stewart and Allen (2002), describing a well-preserved, multi-ringed impact structure within the chalk, which they named the ‘Silverpit Crater’ (Figure 4). Discovered within seismic reflection data in the UK Southern North Sea, they concluded that this crater was formed by an asteroid that impacted between 60 and 65 Mya at the end of the Cretaceous. The formation of concentric ringed 20-km-wide fault scarps encasing a 3-km central crater at such a relatively small scale was not previously thought possible; examples of these concentric ring structures can be found extraterritorially, but over a magnitude greater in diameter.
Conclusions

Despite initial observations, the North Sea Chalk Group has been proven to be more complex than originally thought. There exists velocity inversions and structural irregularities that highlight the requirement to use novel approaches when building the velocity model. We used FWI to highlight subtleties and increase resolution, subsequently improving imaging in the deep. In conjunction with FWI, we were able to apply a modern broadband processing flow to 90s vintage data showing uplift despite short offsets. This improved the continuity of key prospective horizons and helped position sealing faults correctly. We also learned to pay closer attention to chalk, particularly in shallow water when processing. The findings from these two studies will allow us to extend processing from West Wick 2019 into the northwest using data from the Inner Moray Firth 2014 data set and further west on the Cavendish 2019 data set using the Ravenspurn data set. Finally, we rediscovered the Silverpit Crater, showing us that chalk is not an uninteresting, homogeneous mass, but one that should garner a geoscientist’s attention.

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References


