Southern North Sea: unexplored multi-level exploration potential revealed

Karyna Rodriguez[1], Richard Wrigley[1], Neil Hodgson[1*] and Howard Nicholls[1] present a 2D survey that has imaged the Intra-Carboniferous, allowing the Dinantian play in the UK North Sea to be evaluated with confidence.

As exploration evaluations for the 28th UK Licensing round draw to a close, the industry can reflect on the fierce competition for acreage in the Dinantian (Early Carboniferous) play at the northern margin of the Southern Gas Basin. First gas production from the Breagh Field in October 2013, confirming the commerciality of the play, prompted a regional play-fairway study which was quickly followed by the acquisition of a dense 2D seismic programme (Figure 1) in 2013. Intended to define the prospectivity of the Base Permian, this survey has imaged the intra-Carboniferous remarkably well allowing, for the first time, the potential of this sequence to be mapped and evaluated with confidence. Furthermore, post-salt charge modelling and seismic AVO-modelling reveal prospects at higher stratigraphic levels, indicating multi-level exploration potential in an exciting new play-fairway.

Main hydrocarbon plays

The UKCS Southern North Sea has two major NW-SE trending plays defined by Permian (Rotliegend) and Carboniferous gas fields (Figure 2), with the Middle Carboniferous play working to the Northeast where the Rotliegend Sandstone facies is absent. North of the main legacy plays, the northern parts of Quads 42 and 43 have been little explored since the limits of the Rotliegend and Middle Carboniferous plays were established, however, a secondary Triassic Bunter Sandstone play is proven in the Esmond and Forbes Fields.

Due to the geometry of the Base Permian unconformity, the Carboniferous is increasingly eroded to the north (Figure 3) and the section encountered here is the sandstone-rich Dinantian (Early Carboniferous) Yoredale Formation (YF), Scremerston Formation (SF) and the Fell Sandstone Formation (FSF).

The first well into the Breagh field (42/13-2), drilled by Mobil in 1997, encountered the SF which contains reservoir quality channel sandstones with interbedded shales and thin coals, finding 20 m net pay in a 120 m column and testing at non-commercial rates (3 mmscf/d). However, interpreting the low flow rates due to drilling induced reservoir damage, in 2007 Sterling Resources drilled the 42/13-3

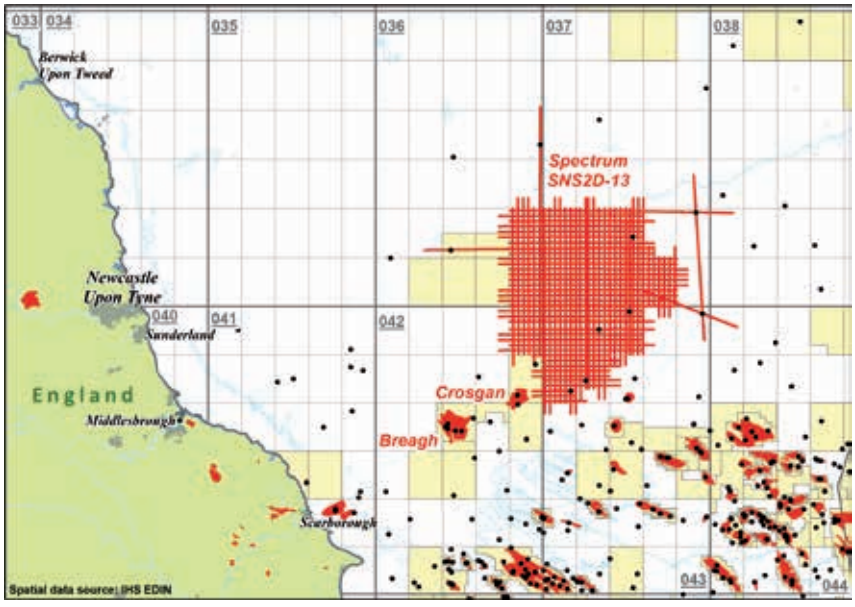

Figure 1 *Spectrum 2013 seismic data.*

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appraisal well that encountered 23 m of net pay in a 90 m column, and without damaging the formation they tested at commercial flow rates (17 mmscf/d). Subsequent appraisals reported up to 26 mmscf/d flow rates (from a horizontal completion), and the field was brought into production in Q3 2013. The adjacent Crosgan field was discovered by Total with well 42/15a-1 in 1990, and awaits appraisal prior to development as a satellite to Breagh. The Breagh 2P Reserves are reported at 604 BCF and P50 contingent resources for Crosgan are 101 BCF respectively, establishing the potential of this new play fairway for significant discoveries.

Regional depth mapping of the base Permian in the northern Gas Basin reveals a generally simple south-dipping monocline, except over the Breagh-Crosgan area, which stands out as a broad high. Little progress was made identifying valid structures on trend to the north-east as legacy seismic data in the region is widely spaced, multi-vintage and generally poor quality due to the geological complexities of the section.

Regional play fairway mapping was first carried out using well data. Although relatively few wells penetrate Dinantian reservoirs, mapping the geology of the base Permian subcrop of the Dinantian across the northern margin of the gas basin had been attempted using published well data (Maynard and Dunay, 1999). This work has been verified by Spectrum in a study of 42 released wells in the area, many of which (for example 41/10-1, 42/10b-2, 42/13-3 & 42/15a-2, 43/5-1) demonstrate the key play elements. A broad NW-SE trend of Early Carboniferous subcrop to base Permian extends through and NE of the Breagh area into open acreage. The limit of the play fairway is defined by wells in the south of Quad 42 and 43 that encountered younger mudstone-prone (Westphalian and Namurian) units that are characterised by sandstones with poor visible porosity and low permeability.

Reservoir, charge and trap key play; elements were mapped using conventional play-fairway analysis. Combining the main play elements into a play-fairway analysis indicates that the low-risk common risk segment of the SF/FSF play fairway extends in a band extending NE from Breagh-Crosgan into open acreage (Figure 4).

This evaluation indicated that the SF play-fairway extended through the area to the NE of Breagh and Crosgan. This supported the acquisition of a new, high-fidelity, dataset in this region. Indeed the quality of this data exceeded expectations allowing a more exhaustive understanding of the key play elements to be derived.

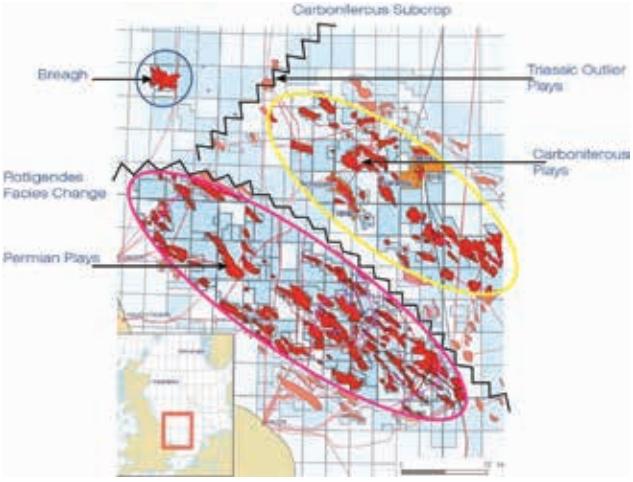

Figure 2 *Permian and Carboniferous play trends.*

2013 seismic data

A total of 4017 km of 2D multi-client data was acquired in late 2013 by Spectrum over open acreage to facilitate exploration of the SF and FSF play fairways, north-east of the Breagh-Crosgan fields. This data was collected with an 8-km cable, nominal 160 fold with 10 second record length. The subsequent processing of the data through a modern, AVO compliant Kirchhoff PSTM sequence was a key factor in denoising the data and enhancing the subsalt image. All data-dependent scaling applications were avoided in the processing sequence. Successive iterations of demultiple techniques, including dual domain Tau-P Decon, delayed-start SRME at top chalk level and high-resolution radon, had the most positive impact at Permian and intra-Carboniferous levels. Close collaboration between interpreters and processors from an early stage identified the top chalk as a generator of strong multiples which masked the deep section. Using SRME to remove these multiples allowed the processors to pick a very accurate velocity field ahead of application of an aggressively targeted pre-PSTM radon.

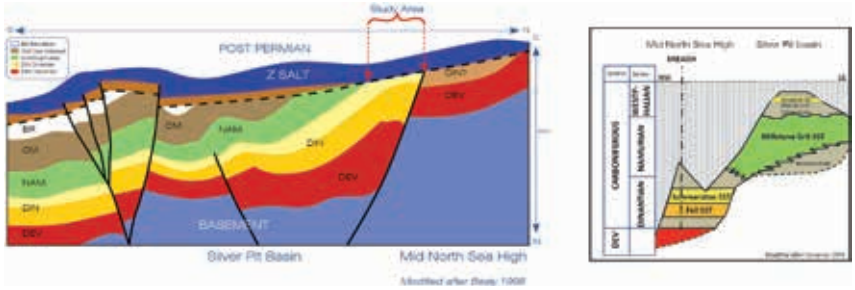

Figure 3 *South-North transect illustrating base Permian unconformity erosional geometry and simplified Carboniferous stratigraphy.*

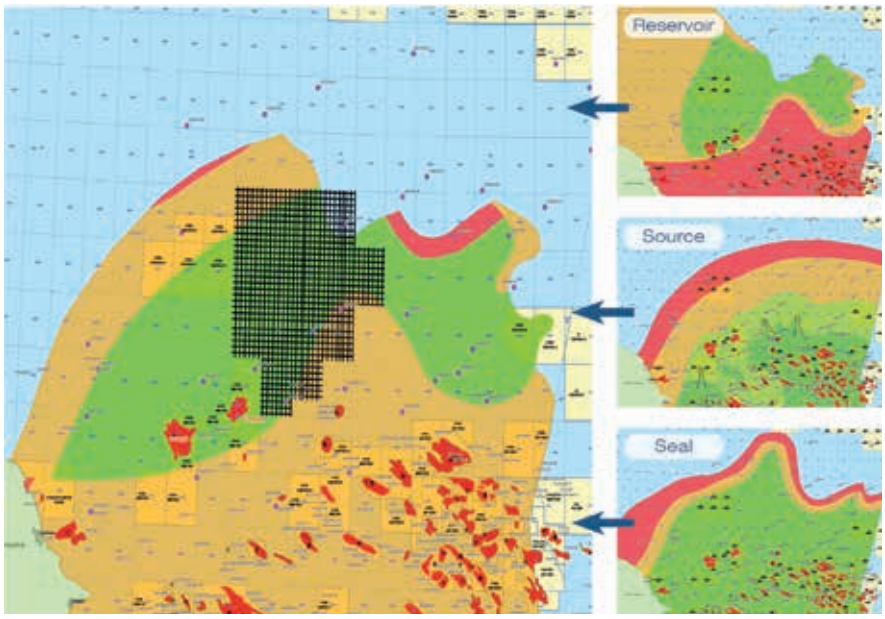

Figure 4 *Composite risk segments map.*

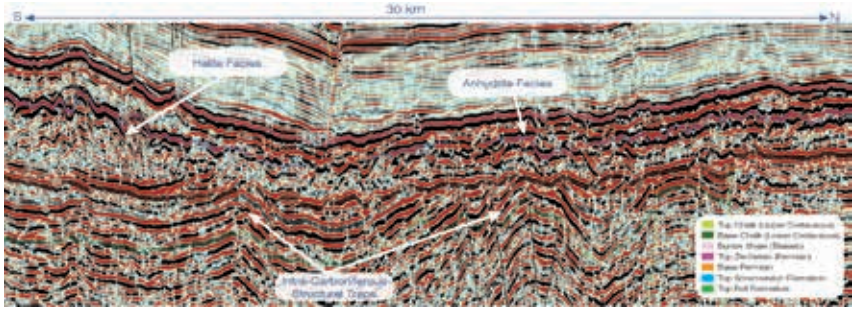

Figure 5 *Seismic section illustrating excellent seismic quality at intra-Carboniferous levels.*

The long record length, together with the innovative processing methodology, targeted at improving the subsalt section, resulted in a dataset of extraordinary seismic quality to be assembled over this area, which images the Triassic, Permian and intra-Carboniferous sections with great clarity, and has allowed base Permian structures (similar to Breagh Field) to be mapped in open acreage and with intra-Carboniferous fault block and independent structural closure potential assessed (Figure 5).

Dinantian play fairway elements

The original focus of this study was to chase the Dinantian subcrop to base Permian play trend extension from Breagh and Crosgan fields. However, during interpretation of the stratigraphically significant horizons (Figure 6), it became evident from well to seismic ties that the SF and FSF had a distinctive seismic character which could be followed confidently over most of the survey, providing for the first time the opportunity to map the long suspected intra-Carboniferous structural traps as well as new unsuspected combined stratigraphic/structural traps.

Reservoir, charge, trap geometry and seal comprise the four key play elements of the Dinantian play.

Dinantian Play 1) Reservoir: SF or the FSF comprise prospective sequences ranging from interbedded sandstones and coals to thick, stacked delta top channels. Interpretation of the new seismic data makes intra-formational facies mapping possible for the first time, highlighting channel belts and reservoir sweet spots. Interbedded SF sandstone and coal sequences are represented by a series of parallel, high amplitude, relatively continuous reflectors to the south and parallel, lower amplitude, more discontinuous horizons to the north. In places, the SF is partly eroded terminating against the base of the Permian unconformity. Thick, stacked delta top channel FSF sequences are characterized by more discontinuous generally lower amplitude reflectors indicative of a more uniform lithology. The sand-rich FSF typically has high N:G sandstones with individual units up to 40m thick and an average porosity of 17% (43/5-1). Both SF and FSF sequences undergo a major seismic facies change implied by an abrupt termination to the north and have a highly disrupted seismic image below thick salt diapirs. Reservoir

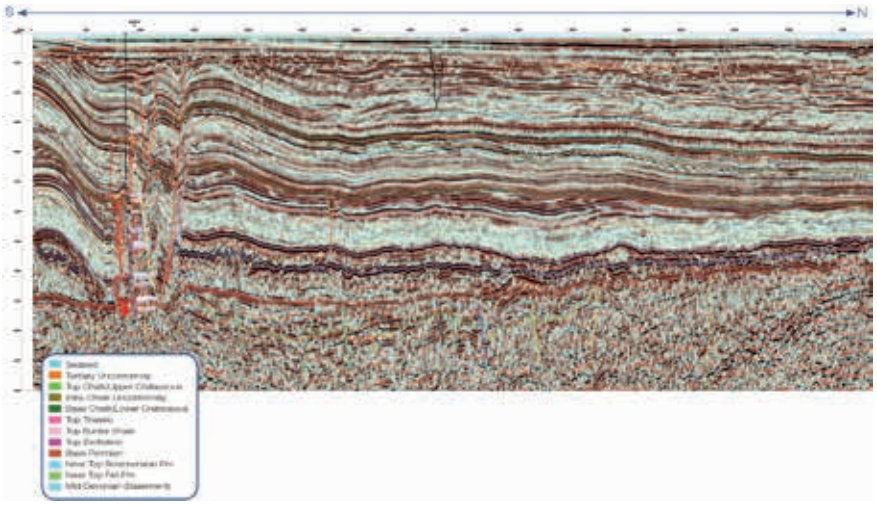

Figure 6 *Main horizons interpreted.*

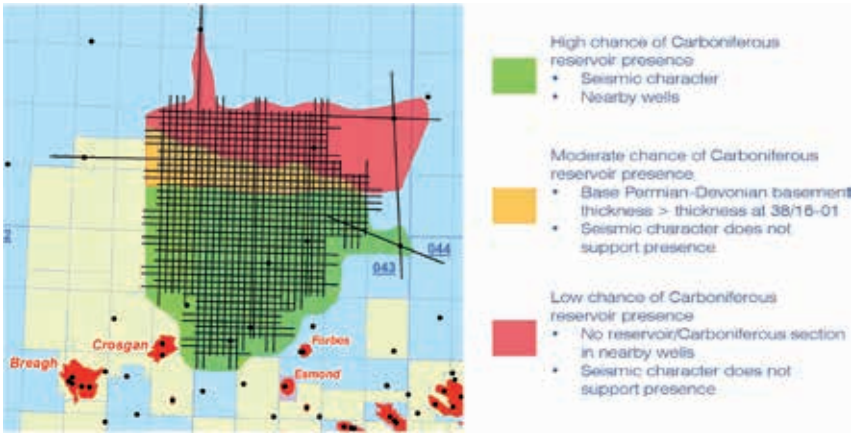

Figure 7 *Presence of Dinantian reservoir risk element map.*

presence was defined based on seismic character and well control (Figure 7).

Dinantian Play 2) Charge: Two main source rocks are postulated. Reservoirs could be charged locally by the Lower Carboniferous Oil Shale Group which includes lacustrine rocks with petroleum source-rock potential (J. Parnell, 1988). The Lower Carboniferous Oil Shale Group source rock distribution should be similar to Dinantian reservoir presence (Figure 7) and is expected to be in the gas generation window considering nearby well temperature data (43/06-01). Alternatively, gas could be sourced from Westphalian Caister and Westoe Coal Formations in the Silver Pit Basin to the south, requiring longer distance migration laterally up-monoclinal dip below the Zechstein salt seal. Such a charge pathway relies on long-distance migration for which no additional information can be obtained from the seismic interpretation carried out in this study.

Dinantian Play 3) Trap: Various structural highs with carboniferous subcrop on trend with Breagh and Crosgan Fields were identified at the base Permian unconformity level. Multiple independent structural closures, fault-closed structures and erosional updip terminations against Zechstein salt were all identified at SF level. Very large one-way fault and three-way dip closed structures as well as independent structural traps are mapped at FSF level. However, variable thickness of the overlying salt sequence and presence of thick Lower Cromer Knoll grabens, has resulted in lateral velocity variation complexities, introducing large uncertainty in structures mapped in time. Base Permian and intra-Carboniferous depth structures have been confirmed by layer cake depth conversion using a reliable mid-point depth versus interval velocity relationship from nearby wells, thereby significantly reducing the risk in trap geometry.

Dinantian Play 4) Seal: SF/FSF base Permian subcrop play top-seal is provided by Zechstein salt, potentially with a stratigraphic erosional unconformity component. The 2013 seismic survey allows detailed facies mapping within the Zechstein sequence, clearly differentiating the halite and anhydrite-dominated sequences. Top seal effectiveness to the Carboniferous is largely dependent on Zechstein facies type. Sub-Permian plays farther north on the Dogger High are likely to have top seal issues due to thin Zechstein, and this is complicated by local halokinesis. Interbedded shales provide

intra-Carboniferous seal potential for tilted fault blocks and anticline structures, and indeed a low reflectivity sequence overlies the SF sequence in places, possibly indicative of higher shale content.

One of the more intriguing applications of the new data has been to map the location of welds in the salt where top seal may be locally challenged (Figure 8) and gas migration may be possible into the Triassic system and even higher stratigraphic levels.

From Dinantian play fairway to multi-level prospectivity

It is in areas where the Zechstein top seal is challenged for the base Permian subcrop play that hydrocarbons have a high chance of migrating from the Carboniferous section up into higher stratigraphic levels. This play concept was established by the nearby Bunter Sandstone discoveries of the Forbes and Esmond gas fields. This understanding has resulted in a gas window analysis in which more than one type of window is recognized and high-graded according to likelihood (Figure 9).

An angle stacks reconnaissance study conducted in parallel to the gas migration window analysis revealed potential AVO/AVA type anomalies with a strong relationship to the migration windows identified. Amplitude anomalies mapped in depth at Bunter Shale and Top Chalk level correlate well to structural closure.

Having identified the prospectivity higher in the stratigraphy, the potential of the Triassic Bunter Sandstone, Lower Cretaceous Sandstone, intra Chalk and top Chalk plays were considered.

Triassic bunter sandstone play: Key play elements include proximity to a gas migration window and presence of Bunter Sandstone (Figure 10). Structural closures are best evaluated and risked when both of these factors are considered together.

Lower Cretaceous Sandstone play: The Lower Cretaceous is mapped as an isolated erosional remnant below the Lower Cretaceous unconformity, updip of a gas migration window. The play is characterized by a strong AVO/AVA-type anomaly with reservoir presence inferred from seismic acoustic impedance character and supported by presence in several wells in the area, notably in the Breagh and Crosgan Fields (Figure 11).

Intra-chalk plays: Near several of the intra-Chalk horizons with possible AVO/AVA-type anomalies, a very clear

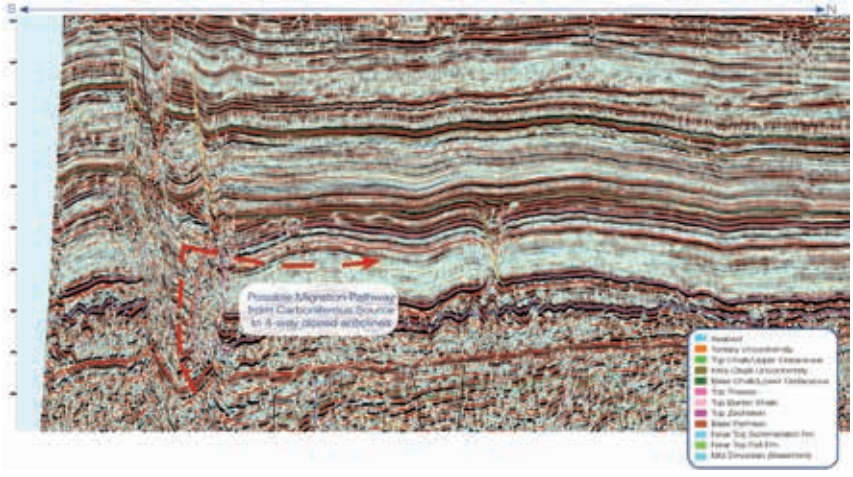

Figure 8 *Seal compromised by possible gas migration window on seismic section.*

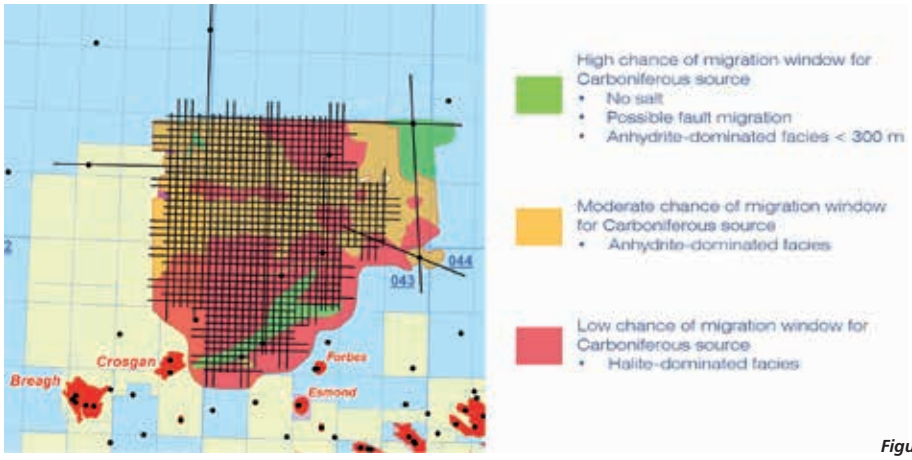

Figure 9 *Hydrocarbon window analysis.*

intra-Chalk unconformity was identified and mapped. A thickness map between this unconformity and top Chalk exposed a series of erosional levee channels and inner-outer slope fan channel complexes (Figure 12). Main reservoir provenance above the unconformity is inferred to be from a palaeoshelf to the SW, with ample well and seismic evidence of a relative lowstand in an inner-outer slope setting suggesting high sand content. AVA-type amplitude anomalies of the horizon just above the unconformity were gridded to identify trends and appeared to be concentrated within the channels, on the levees and in mounds within the slope fan complexes. This play relies on gas migration from a down-dip hydrocarbon window towards the NE.

Top chalk play: Several untested structural closures near potential hydrocarbon windows were identified. Some have AVO/AVA-type anomalies which seem to conform to structure.

Pre-stack seismic inversion

The remarkably good seismic quality at intra-Carboniferous level facilitated using subsalt pre-stack seismic inversion, over four test lines that intersected two wells which had

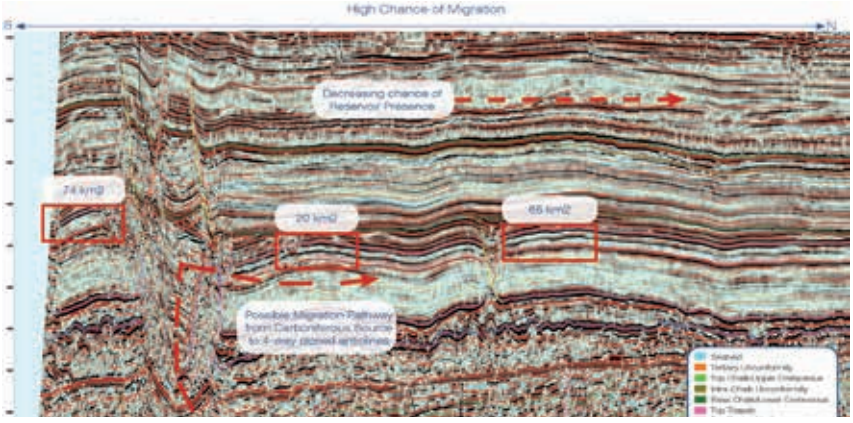

Figure 10 *Triassic gas migration windows and bunter sandstone presence.*

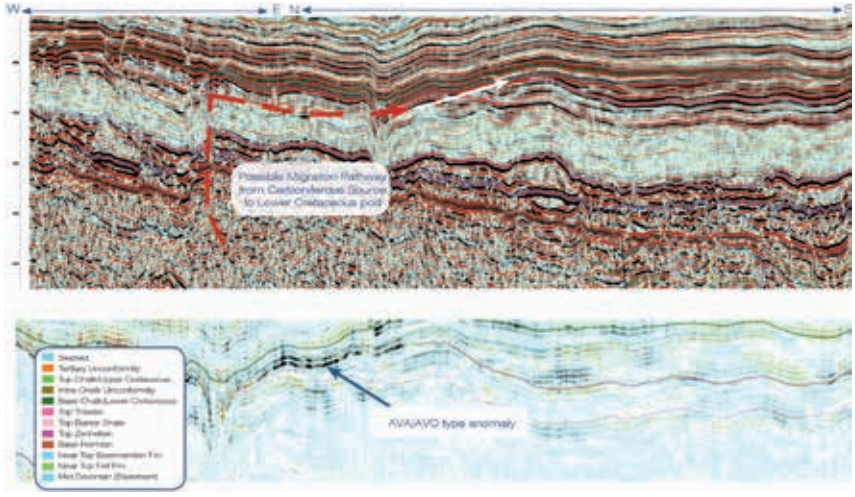

Figure 11 *Lower Cretaceous AVA type anomaly.*

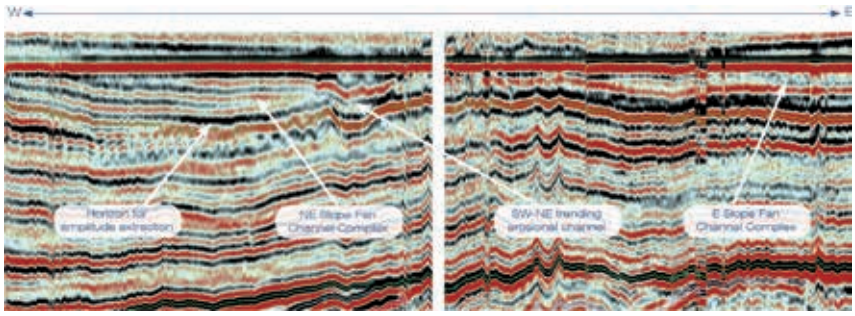

Figure 12 *Intra-chalk channels and slope fan complexes on section flattened at top chalk level*

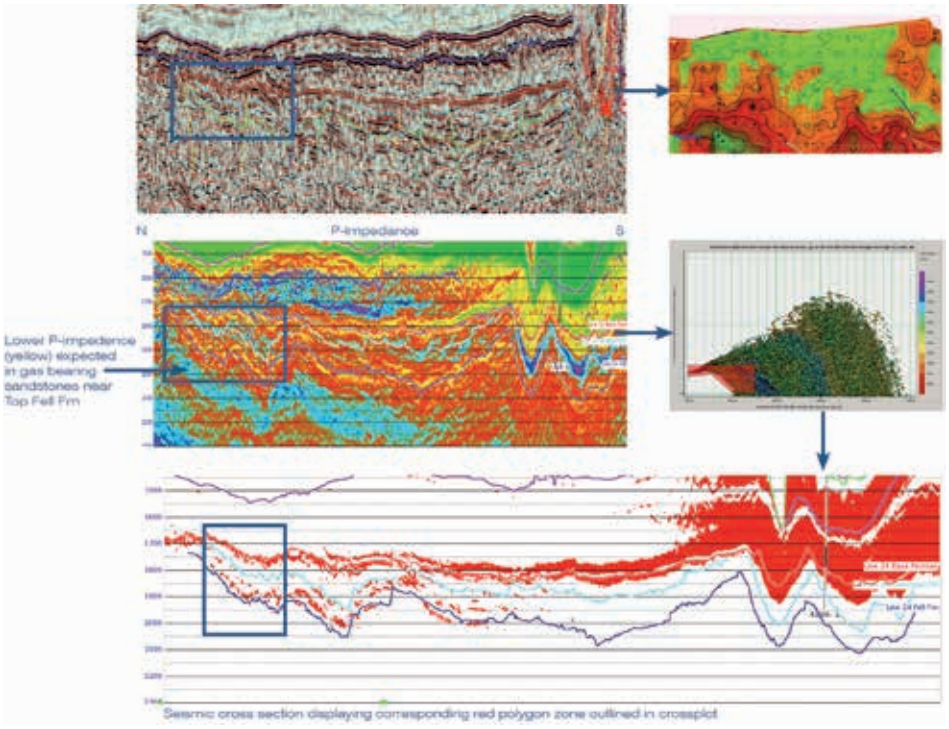

Figure 13 *Pre-stack inversion results.*

encountered SF and FSF. A very encouraging result was obtained (Figure 13) conforming to one of the largest intra-carboniferous leads identified. Although preliminary, this suggests that the method provides an additional tool to increase confidence in the Dinantian play fairway.

Summary

Modern, dense, high-quality 2D seismic data integrated with regional well control has allowed a detailed understanding of the Dinantian playfairway to be developed. A comprehensive prospectivity analysis for both the long-suspected base Permian subcrop and new intra-Carboniferous play have been completed. Careful layer cake depth conversion and risk element analysis using the well and seismic evidence allowed risked potential resource estimates to be obtained and used to confidently high-grade the numerous leads identified. Finally, positive pre-stack inversion results are found to give additional support to some of the identified prospects.

Recognition of migration windows and AVA-type anomalies led to an unpredicted outcome in this study, the identification and quantification of other play types at Triassic, Lower Cretaceous and Chalk levels.

Conclusions

What started as a Dinantian play fairway analysis evolved through a seismic acquisition phase into a full-scale multi-level prospectivity review extending the limits of established fairways and developing new untested fairways. New, high-quality, dense 2D seismic has been a critical component in successfully high-gradins the prospectivity of these plays that were previously unimaged on poor quality legacy seismic. This new tool enables explorers to develop a detailed regional understanding of the Dinantian as well as intra-Carboniferous, Triassic, Lower Cretaceous and intra-Chalk plays. To date, more than 750 bcf of hydrocarbons have been discovered in the Dinantian play-fairway, the YTF potential identified in this study alone is more than 1 tcf – a significant and valuable potential lying so close to the infrastructure of the mature Permian and Carboniferous basins to the south.

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