West of Shetland exploration unravelled – an indication of what the future may hold

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Introduction
Exploration west of the Shetlands began in 1972, but it was not until the 17th exploration well in 1977 that the first discovery, Clair, was made. Although a number of commercial discoveries have been made since then, the overall exploration success rate of approximately one in five has been generally disappointing. This is a consequence of a number of factors that are reviewed below. Loizou (2003a) concluded that the majority of the failed wells with Palaeocene objectives from 1995 were due to invalidity of the trap. This paper reviews the historical exploration success history and provides an analysis of all 138 exploration wells from 1972 to the end of 2004 (Figures 1 and 2).

Brief exploration success
Hydrocarbon shows have been encountered West of Shetland at all stratigraphic levels from Devonian to Eocene (Figure 3). The initial exploration in the 1970s focused on simple tilted fault traps (analogous to the North Sea) identified on poor quality 2D seismic data in relatively shallow water (<500 m) along the SE flank of the Faroe-Shetland Basin. Clair (six billion barrels STOIIP) and Victory fields were discovered during this exploration phase in Devonian-Carboniferous and Early Cretaceous sandstones respectively. These hydrocarbon pools were not, however, developed at that time due to low productivity from the relatively tight fractured reservoir in Clair and sub-economic gas volumes in Victory. Neither the technology nor the infrastructure was in place to exploit these discoveries.

Clair discovery well 206/8-1A tested 25° API oil at 1502 b/d of oil and remains the largest oil discovery in terms of STOIIP on the UK Continental Shelf. The Clair structure comprises an elongated NE-SW trending ridge of Lewisian basement and an associated terrace or rollover of variable-quality Devonian-Carboniferous continental red beds. Intriguingly, the 206/8-1A well was actually targeting Jurassic/Cretaceous sands, but penetrated a 700 m section of Carboniferous to Devonian clastics directly below thick Upper Cretaceous mudstones. The upper 568 m of this sequence was oil bearing. Following the acquisition of 3D seismic data in the late 90s over the central area of the Clair discovery and subsequently over the adjoining area, a significant improvement ensued in the understanding and visualization of the structure. Advances in technology and increase in the oil price have improved the economics for the first phased development of Clair to exploit 250 million barrels of oil reserves.

During 1977 there were two further discoveries, both in the Lower Cretaceous. The Victory field was discovered by the 207/1-3 well, which encountered 68 m of gas-charged Lower Cretaceous sandstones at a shallow subsea depth of 1096 m in an easterly dipping rotated fault block covering an area of approximately 10 km². Well 206/11-1 located in the hanging wall, rollover of the Rona Ridge Fault encountered gas at 3501 m TVDSS within a small independent structural closure. Other nearby but later Lower Cretaceous tests, such as 206/5-2, 206/4-1, and 206/8-6a, failed mainly as a result of invalid structural closure.

The Victory Field is estimated to contain between 200-250 billion ft³ of gas-in-place, which is presently considered to be insufficient to support a stand-alone development. However, Victory may in future contribute to a regional gas development strategy being considered for the deep water...

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Ultimately, the commercialisation of the Victory gas will depend upon a more successful regional exploration programme.

During the 1980s, advances in drilling technology shifted the exploration activity further offshore into deeper waters (350-750 m) of the Flett Sub Basin, with the focus on Palaeocene structural/stratigraphic traps and pre-Tertiary tilted fault block structures (mainly identified on 2D seismic data). Only the Laggan 206/1-2 discovery of 1986 can be counted as a ‘significant’ discovery from this phase. The other successes (204/30-1, 219/28-2Z, and 214/27-1) are smaller, sub-economic, gas pools (<150 billion ft$^3$ pool size) located along the Flett Ridge within the Palaeocene. Exploration interest waned through the late 1980s with the continued lack of success. By the end of the 1980s none of the West of Shetlands finds had been successfully taken forward to sanction.

In 1990, the Triassic Strathmore (well 205/26a-3) discovery was made, closely followed by the Upper Jurassic Solan discovery (well 205/26a-4) the following year. These discoveries demonstrated the prospectivity of the East Solan Basin and similar back basins along the same trend. Exploration for potential Solan analogues requires the preservation of sufficient Late Jurassic section to be confident that the thickening is due to Solan Sandstone basin-floor sandstone presence. Identifying Strathmore analogues is less straightforward. The reservoir is regionally extensive, but it is difficult to define seismically without biosтратigraphic control (rare in the Triassic) or nearby penetrations of Triassic sandstone, which are few and far between (Herries et al., 1999). The East Solan Basin discoveries prove the play concept, but the volumes of hydrocarbons generated by the back basins still remain one of the limiting factors for further exploration.

Significant advances in seismic technology in the early 1990s led to the basin-opening discovery of Foinaven in 1990. The 204/24-1A well discovered an oil and gas column, within 10 m net of high quality, Palaeocene, submarine fan sandstones. The discovery of Foinaven fundamentally shifted much of the focus of exploration towards the Palaeocene.
Industry success in areas such as the Gulf of Mexico using modelling such as amplitude variation with offset (AVO), and improvements in seismic processing techniques allowed direct hydrocarbon indicators to be identified on the seismic data for the first time. Allied with the acquisition of 3D seismic surveys, these techniques contributed to the successful exploration of the Palaeocene oil play in the Quadrant 204 area with the subsequent discoveries of Arkle, Schiehallion, Cuillin, Loyal, and East Foinaven. This led to a significant competition for 16th Round licences and an upsurge in exploration activity on the Atlantic Margin, which peaked in 1996.

The main Palaeocene T31-T35 oil accumulations in Quadrant 204 occur in the proximal submarine fan depositional systems near the axis of the Westray Ridge Inversion. Traps contain both structural and stratigraphic elements. The structural elements include dip and fault seal against E-W trending faults, and lateral seal is generally provided by shale-out zones and truncation/erosion by younger shale filled slope channels. Regionally extensive T35 shales provide top seal.

Exploration of the 16th Round awards (1995) has had generally disappointing results, and led to no success in extending the Palaeocene play away from the BP/Shell discoveries in the Foinaven sub-basin. Six of the wells (204/14-1, 204/24-2A, 204/25a-2, 205/16-2, 206/13, and 206/9-2A) are by and large appraisal wells. The 1998 Conoco well 204/14-1, for instance, was located approximately 1.25 km NE and slightly downdip of the 204/19-8Z Suilven discovery well. Since it was located within the established OWC encountered in the 204/19-8Z discovery well, it could be considered as a simple appraisal of Suilven. Included in the table are four small gas discoveries (205/23-2, 206/2-1A, 206/11-1, and 219/28-2Z) and also the heavy oil 204/28-1 discovery.

Of the 138 wells, approximately 65% were positioned on sparse 2D seismic data, which was often very poor in encountered gas bearing Jurassic sandstones within a shallow anticlinal structure on the Rona Ridge (683 m TVDSS).

Since the dawn of the new millennium there have been three interesting discoveries. During 2000, the 214/9-1 well encountered gas bearing Upper Palaeocene sands. Well 204/10-1 encountered hydrocarbons within the Upper Palaeocene on a prospect referred to as Cambo, which is a large structural four-way dip closure, draped over a pre-Cambrian basement high. Most recently, well 213/27-1Z (Rosebank/Lochnagar) encountered two oil and gas accumulations with a total net pay of 52 m, with oil quality ranging from 27-36° API.

Who drilled the exploration wells?

The distribution of the 138 West of Shetland exploration wells is shown in Figure 2 with the drilling history summarized in Figure 4. Many of the wells were licence obligations, with approximately 30 encountering notable hydrocarbons (Table 1). Six of the wells (204/14-1, 204/24-2A, 204/25a-2, 205/16-2, 206/13, and 206/9-2A) are by and large appraisal wells. The 1998 Conoco well 204/14-1, for instance, was located approximately 1.25 km NE and slightly downdip of the 204/19-8Z Suilven discovery well. Since it was located within the established OWC encountered in the 204/19-8Z discovery well, it could be considered as a simple appraisal of Suilven. Included in the table are four small gas discoveries (205/23-2, 206/2-1A, 206/11-1, and 219/28-2Z) and also the heavy oil 204/28-1 discovery.
quality. The positioning of approximately 25% of wells was based on weak and somewhat flawed geologic concepts (Loizou, 2003b). Several of the dry holes can be attributed to simultaneous or back-to-back exploration drilling, testing similar play concepts over a short time period (examples include wells located on 16th Round licences). The inability to quickly trade well data appears to be one of the contributory factors toward the 10 dry holes in Quadrant 202. Not surprisingly, the key geologic explanation for approximately 66% of the failed exploration wells relates to the trap being fundamentally ineffective.

Over the last 32 years, 25 different operators (BNOC and Britoil counted here as one operator) have drilled the 138 exploration wells. Only 13 of the 25 operators have drilled the 30 successful exploration wells. BP have been the most successful (Figure 5), although 10 of their 12 discoveries from 33 exploration wells are located near or within the Foinaven area. Six other major companies have each operated more than eight exploration wells. These companies have drilled 56 (40%) of the exploration wells with just a meagre seven discoveries between them (combined overall success rate of 12.5%).

Eight companies each operated between three to six exploration wells with a combined total of 10 discoveries from 36 wells. The overall success rate for these eight companies is one in four. Figure 6 shows that the remaining 10 companies that operated either one or two exploration wells (total of 13 exploration wells) made just one discovery between them. Once more their combined success rate is poor, just one in 13.

Analysis of failed wells
Analysis of the key geologic reasons for success or failure of wells (e.g. trap, reservoir or charge) can provide insight into which factors are essential for trapping 'commercial' quantities of hydrocarbons. The description 'success' is defined here as a hydrocarbon accumulation that if tested would flow to surface. It does not necessarily indicate the commercial potential of the discovery.

The evaluation of the 138 West of Shetland exploration wells demonstrates that generally there is a need for better understanding of play concepts, trapping mechanisms, charge history, and source distribution. Even today, this lack of knowledge is not helped by the inability to quickly trade well data, which contributes to a reduced understanding of the area, and ultimately impinges on success rate.

The post-drill analysis of the failed wells forms the basis of this study. Each well has been assessed in terms of the key trap elements (i.e. trap, reservoir, seal, and charge). The key reason for most failures West of Shetland has been poor trap definition. However, many wells failed on a combination of geologic components (trap, reservoir, seal, and source). For this analysis, if the trap constituted more than 50% towards the well failing to find hydrocarbons, then trap is assigned as the key element for failure. Figure 7 shows the distribution of the key elements of failure for the 138 failed wells. The majority of wells (66%) are deduced to have failed as a result of a poorly defined trap; 21% of the wells failed as a result of thin or absent reservoir, and 6% failed due to the seal being either thin or absent. Intriguingly, only 7% of the wells specifically failed as a result of source rock absence. However, many poorly defined traps have also failed due to lack of migration.
Exploration west of the Shetlands can be grouped into three gross play categories, namely the Eocene, Palaeocene and the Mesozoic. The following section is a summary focusing mainly on the failures.

**Eocene exploration**

Although the Eocene has been penetrated by every exploration well, only three wells were specifically positioned on Eocene prospects – 214/4-1, 214/23-1, and 214/26-1 (Figure 2 shows the position of these wells). The 214/4-1 well was located on a robust, mid-Eocene, four-way dip closure with a conspicuous flat spot and encountered a significant gas accumulation. Well 214/23-1 penetrated the edge of a large robust four-way dip trap, although sourcing is considered the principle reason for failure. However, the well is located on the outer perimeter of the Eocene closure, which would imply that the trap was not fully tested. The 214/26-1 well appears to have failed on a combination of trap reliability and sourcing.

**Palaeocene exploration**

Over half of all exploration wells (73) West of Shetland have mainly targeted Palaeocene traps, with 47 containing a significant stratigraphic component (Loizou et al., 2005). Nineteen of the wells (27%) encountered hydrocarbons (Figure 8). Of the 73% of failures, 59% were positioned on poor traps, 7% are attributed to thin or absent reservoir, and the remaining 7% to poor seal.

Only three out of the 73 wells appear to have been positioned on a robust Palaeocene ‘structural high’, and all of these encountered notable hydrocarbons. Interestingly, these wells, 204/10-1, 213/27-1Z, and 214/9-1, are all located along the Corona Ridge.

**Exploration of Palaeocene stratigraphic traps**

A total of 44 exploration and three appraisal wells West of Shetland (Loizou et al., 2005) are considered to have targeted Palaeocene traps with a significant stratigraphic component (Figure 9). Analysis shows that all of the successful wells are located close to or at the basin margin, with seven discoveries located in the Foinaven Sub-basin (Foinaven, South-east Foinaven, Schiehallion, Loyal, Alligin, Cuillin, and Arkle) and a further three located in the Flett Sub-basin (Laggan, Torridon, and 214/30-1). The Flett Sub-basin discoveries all lie immediately west of the Flett Ridge (Figure 2). Most of these discoveries have a northwesterly structural dip and are sealed up-dip by an E-W or NE-SW fault in combination with stratigraphic pinch-out of the Vaila sandstones.

Of the 38 failed wells, around 71% were positioned too far updip to trap hydrocarbons, and the remainder were positioned downdip of any trapping potential (Figures 9 and 10). Quite surprisingly, none of the failed wells are considered to have tested what constitutes a valid stratigraphic trap. A further breakdown of the Palaeocene stratigraphic wells is shown on Figure 11. About one in 5 wells were successful (21%). Approximately 27% of the wells failed due to no seal or reservoir, and a further 19% encountered reservoir but no seal. Around 23% had reservoir but were located too far downdip, and 10% had a seal but no reservoir.
Approximately 40 wells were positioned on an amplitude or AVO anomaly. Of these, nine encountered notable hydrocarbons. Following post-mortem studies, the majority of the 30 wells that failed to find hydrocarbons could be shown to represent poorly defined amplitude anomalies (various lithologies including igneous), AVO artefacts, and spurious DHIs (which include multiples). What became a geophysically led exploration emphasis often lost sight of geology, and it is evident from this analysis that the seismic driven exploration risk reduction is not a solution (Parr et al., 1999). Companies have positioned several of the wells drilled during the last 10 years on what they regarded as Class III AVO anomalies. Alarmingly, recent analysis of just the basic offset stack seismic data for two wells clearly shows that these had high amplitudes on the near (low offset) but relatively little or no high amplitude on the high (far offsets). Furthermore, AVO cross plots and various attribute analyses show no evidence of hydrocarbon presence, and these features are in effect Class I AVO anomalies.

For a large number of the failed wells that were positioned on inferred AVO or high amplitude features, the companies interpreted these as coinciding with the terminations or up dip limit/pinch-out edge of a sandstone interval. Furthermore, work carried out on these features implied that a hydrocarbon accumulation was present. For most of the failed cases, the cause of the AVO or high amplitude features was misinterpreted or poorly evaluated with respect to the data available at the time.

**Mesozoic exploration**

Sixty-two wells were primarily positioned on Mesozoic and older prospects (Figure 12) of which eight (13%) encountered hydrocarbons. Approximately 46% of the failed wells were positioned on invalid traps, 25% are attributed to thin or absent reservoir, 3% had a general lack of seal and 13% are attributed to charge (the five failed wells in Quadrant 202 are mainly attributed to source).

Overall, the success for the Mesozoic and older prospects has been rather limited. The key discoveries have been Clair, Victory, Solan, Strathmore, and most recently the 2004 ChevronTexaco Lochnagar 213/27-1Z well. Surprisingly, only 11 wells have been positioned on 3D seismic data (204/15-2, 204/19-9, 205/27-2, 206/4-1, 206/5-2, 206/16-1, 213/23-1, 213/27-1Z, 214/9-1, 214/17-1, and 219/21-1), with two discoveries (Figure 2 and Figure 13). Aside from the 213/27-1Z well, the only other 3D success was the 1998 205/23-2 well, which encountered gas-bearing Jurassic Rona sandstones on the Rona Ridge. A number of the other wells encountered hydrocarbon shows.

There has been limited drilling on the Corona Ridge, mainly due to a combination of significant water depth (700 to 1800 m) and the resolution of the late 90’s UK/Faroes median line. Nonetheless, all four wells located on the Corona Ridge (Figure 2) that penetrated a pre-Tertiary section have encountered hydrocarbons - including the significant 213/27-1Z discovery.

**Examples of failed Mesozoic wells**

Wells 206/3-1 (2D seismic) and 206/4-1 (3D) both targeted a Turonian interval, and penetrated 300 m and 500 m of Turonian sandstones respectively that are hydrostatically...
pressed, suggesting communication up-dip with the Rona Ridge (Grant et al., 1999). The presence of oil and gas suggests a conduit and key migration route for hydrocarbons out of the Foula sub-basin kitchen and into the nearby Clair field. Generally, there is an absence of significant four-way dip closed structures and an apparent absence of fault seal in terrace blocks west of the Rona Ridge. The likelihood of finding commercial accumulations of trapped hydrocarbons in the Turonian interval requires the identification of valid traps.

Well 204/19-9 was drilled in 1996 to test Lower Cretaceous (K40) and Lower-Middle Jurassic onlap plays on the eastern flank of a structural feature referred to as the Morven High. Minor hydrocarbons were encountered over 100 m of the Mesozoic section. In addition, high viscosity immovable bitumen was observed in sidewall cores from the basal sandstone and has been interpreted to be the result of either biodegradation or depressurization of the reservoir due to failure of top seal.

Well 205/27-2 was positioned on what was believed to be an analogue structure of the Solan Field, which contains good quality Upper Jurassic Solan sandstones. Instead, poor reservoir quality Rona sandstones were encountered. However, more recent interpretation suggests that the trap was poorly defined, and that the Solan sandstones can be inferred to be present about 2 km to the southeast of the well.

**Conclusions**

Individually, exploration wells, whether successful or unsuccessful, do not give an accurate or true picture of success. Having analyzed all of the West of Shetland wells, an interesting 138-piece jigsaw provides a more reliable pointer towards potential future success. From the post-drill analysis of the failed wells, the majority (66%) are a result of a poorly defined trap; 21% of the wells failed as a result of thin or absent reservoir, and 6% failed due to the seal being either thin or absent. Intriguingly, only 7% of the wells specifically failed as a result of source rock absence. The wells positioned on ‘valid traps’ have resulted in a success rate greater than 40%. Undoubtedly, this firmly demonstrates that there is opportunity to improve the exploration success rate West of Shetland. Nonetheless, the explorationists must, in future, carefully examine and correctly evaluate all the pertinent data to unravel and understand the true geology that would help create a valid trap, and hence increase the chance of finding commercial hydrocarbons.

Without doubt, the evaluation also of proven examples of successful traps like Clair, Foinaven, Schiehallion, Laggan, Rosebank/Lochnagar, and also analogues from other parts of the world can add value to successful future exploration. However, to improve the future exploration success rate, there is a need for a fundamental awareness and understanding of the key ingredients that constitute a successful trap. Utilizing the appropriate data, robust traps can be successfully mapped with a high degree of confidence. Moreover, if all the right ingredients are present in any area, then the future for that area should be viewed as optimistically bright.

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**References**


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**Figure 13** Success/failure analysis of Mesozoic wells positioned on 2D and 3D seismic data, West of Shetland.