UCG Potential of CNR’s Kincardine Licence, Firth of Forth, Scotland

A Review of the potential and resource estimation for Underground Coal Gasification in Cluff Natural Resources acreage around Kincardine in the Firth-of-Forth, Scotland.

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<td>11th November</td>
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1 Introduction

1.1 Project Background

The UK has large reserves of indigenous coal deposits both onshore and offshore in the Southern North Sea. Carboniferous coal deposits in Central Scotland have been recognised and exploited underground since medieval times and have been mined on a large commercial scale from the mid-18th Century to the early 21st Century. The study area is located in the cusp between the Clackmannan and Dunfermline Coalfields (Figure 1.1), two of the most intensively mined coalfields in Central Scotland.

![Map of Scottish Midland Valley, showing the location of major coalfields in relation to the project AOI (outlined in red).]

The potential for in situ extraction of gaseous hydrocarbons from this coal resource was recognised in the early 1990s with the commencement of Coal Bed Methane (CBM) operations which continue to the present day, immediately to the west of, and slightly overlapping with, the current project area.

Since the cessation of coal mining at Longannet Colliery in 2001, and following reported successful pilot tests in Australia, interest has been growing in the potential for near-shore development of Underground Coal Gasification (UCG) in the deep and unmined coal resource of the Firth of Forth.
Mining licences have been awarded to UCG operators including Thornton New Energy Ltd, Riverside Energy Ltd and Cluff Natural Resources Ltd (CNR).

CNR’s Kincardine licence lies in the Midland Valley of Scotland (MVS) – a southwest-northeast trending basin cutting the central belt of Scotland (Figure 1.1). The MVS is around 80km wide, extends roughly 150km onshore across Scotland and is a major population centre with five of Scotland’s seven cities lying within it.

In July 2014, CNR commissioned Belltree Ltd to carry out a study into the potential for an UCG pilot in the Kincardine area of the Firth of Forth. CNR has a 100% working interest in a licence from the UK Coal Authority consisting of an area of 3,687 hectares (Figure 1.2). An Area Of Interest (AOI), extending c.2km around the licence, was defined by Belltree in which detailed geological assessment has taken place and puts CNR’s licence into a broader regional context.

1.2 Objectives
The aim of this project is to analyse the geological conditions for CNR’s Kincardine licence and to identify geologically continuous coal resources which: are potentially exploitable by horizontal drilling from onshore locations; occur in the depth range 500-1500 m; and which are sufficiently material for successful execution of a pilot UCG test.

1.3 Methodology
A geo-spatial database (developed in ArcGIS software) forms the core of data collation. Input into the database was obtained from various data sources including:

Figure 1.2 Location of Kincardine UCG licence and area of interest defined for the project.
1.50,000 and 1:10,000 surface geology maps published by the British Geological Survey (BGS);
- Scanned hardcopy abandonment plans of charted underground coal and ironstone mines
- Borehole data relating to drilling for water, coal and hydrocarbons acquired from the British Geological Survey and agents of the UK Government’s Department of Energy and Climate Change;
- Historical (public domain) 2D seismic purchased from the UK Onshore Geophysical Library (UKOGL) and BGS, together with an interpretation of that data made for the project by Belltree; and
- Scanned hardcopy mine abandonment plans purchased from the Coal Authority for all coal seams known to have been mined within the Kincardine licence in the Upper Limestone Formation and Limestone Coal Formation with seam thicknesses regularly exceeding 1.8 m; and
- Digitised polygons of all known and probable workings in all seams worked within the AOI purchased from the Coal Authority.

Analysis of additional published data (e.g. coal thicknesses and geochemistry) leading to resource estimation and identification of potential drilling locations was made in the context of this standardised framework.

1.4 Introduction to UCG

Coal has been used as a source of energy for nearly 3000 years but did not become an important source of fuel until the industrial revolution. The world reserves of coal significantly exceed those of oil and gas with a recent estimate of resource (i.e. both economic and uneconomic coal) set at 18 trillion tons (Bhutto et al, 2013). Only one sixth of the world’s coal is economically accessible by traditional methods and current production, after decline in the late 20th century, is on the rise.

UCG is one of several methods to access energy in coal without requiring traditional mining. This can enable coals that are too deep, too thin or otherwise uneconomic to be targeted and exploited. It is one of a number of ‘clean-coal technologies’ which enable the removal of sulphur and nitrogen oxides before, during or after the coal is burned or involve the conversion of coal to gas or liquid fuel. It is a simple concept but in reality it has proved more difficult. The process involves the partial combustion of coal using two wells – one supplying oxygen and water/steam to maintain the burn and the other to bring the produced gas to the surface. The produced combustible gas has numerous uses including power generation, industrial heating or the manufacture of hydrogen, synthetic natural gas or other chemicals.

The concept of UCG is long-standing having been originally developed in the UK in 1868 by Sir William Siemens who suggested gasification of waste and slack coal in a mine (UCG Association website). For the following decades research was ongoing to further develop Siemens’ concept with the first experimental work beginning in 1912 but little progress was made until the Skochinsky Institute of Mining ran a research and development program in the 1930’s. Since then there have been a number of key trials across several continents. In the last 30 years, the most significant developments are Rocky Mountain 1 in the USA (late 1980s), the El Tremedal trials in Spain (1990s) and Chinchilla Development in Eastern Australia (2013).
The two main methods for production of UCG are; through two linked vertical wells and a process called controlled retraction injection point (CRIP) using two horizontal wells. CRIP technology has several benefits; is suitable for thin, deep coal seams and, in comparison to the two vertical-well production method, results in a higher quality of gas produced, reduces the heat loss during production and improves the overall efficiency of the UCG process (Bhutto et al, 2013). Coals are worked in rectangular panels, the size of which is designed early in the well planning stage.
2 Geology

2.1 Geological Overview
Geologically, CNR's Kincardine licence lies within the northeast-southwest trending Midland Valley of Scotland, an area of low-lying ground approximately 80km (50 miles) wide. The parallel Highland Boundary and Southern Uplands Faults respectively separate the Midland Valley from the Lower Palaeozoic and older metamorphic terrain of the Grampian Highlands and the relatively unmetamorphosed Lower Palaeozoic ocean trench sequence of the Southern Uplands (Figure 2.1).

The Midland Valley has complex origins prior to the mid-Devonian, with major sinistral strike-slip and thrust movement on both bounding faults. These early northeast-southwest movements and structural features are referred to in geological literature as ‘Caledonian’, and are associated with the closure of the Iapetus Ocean and resulting oblique continental collision. Since the mid-Devonian, the Midland Valley has behaved as a simple, graben-type depositional basin, with occasional reactivation within the basin of normal and strike-slip faulting along inherited Caledonian structures. Little is known of the pre-Devonian basement to the Midland Valley and it is the subject of active geological and geophysical research.

Amongst the earliest known rocks in this area are the lavas of the Ochil Hills (Lower Devonian) which outcrop about 12 km to the north of the licence on the upthrown side of the Ochil Fault. These lavas are succeeded by thick Lower and Upper Devonian red-bed sediments, deposited in a major inland sedimentary basin and are known (through deep drilling at Inch of Ferryton) to exist south of the Ochil Fault and within the AOI at depths in excess of 6500ft.

The rift or graben structure of the present Midland Valley formed during the Carboniferous, when lithospheric tensional stretching caused periodic crustal sags and resulting cycles of shallow water marine incursions and fluvial-dominated delta sequences. During the early Carboniferous, deltas and associated fluvial systems flowed into the Kincardine area from the northwest and northeast and were channelled into a single major fluvial system prograding to the west-southwest. The Midland Valley was one of many similar basins developing in Britain at this time (Figure 2.1).
Figure 2.1. Location of the Midland Valley of Scotland (MVS) in relation to principal structural features of the British Isles that had significant influence on the deposition of Lower and earliest Upper Carboniferous strata. Adapted from Waters et al (2007).

In the Midland Valley, there is a close spatial relationship between the location of major sedimentary basin areas and synclinal structures, and between intervening thinner block sequences and anticlinal
structures. These structures were initiated not so much as conventional stress-related folds, but rather sags and drapes related to tensional stretching of basement (although the axes of the basins and blocks are normally offset to some degree and are enhanced and affected by subsequent stress-related folding). The AOI is located on the eastern limb of one such Carboniferous synclinal structure, known as the Clackmannan Syncline.

Syn-sedimentary ‘folding’ is often associated with growth faulting in areas of rapid accumulation of shallow water deltaic sequences. In this region, the Ochil Fault is a spectacular example of a growth fault; having a cumulative throw of some 3000 m, much of which occurred during the Carboniferous (it is still associated with deep seismic activity today).

Because of the stretching process, volcanism was common in the Carboniferous, and there is much evidence of intrusive (dolerite sills and volcanic necks) and extrusive (tuffs and basalt lavas) igneous activity within Carboniferous sediments throughout region.

Little is known of the geological history of the district during the interval between Carboniferous times and the Quaternary. Permian terrigenous sediments were almost certainly deposited at Kincardine but, together with much of the Upper Carboniferous, have been removed by erosion. Evidence from the offshore Forth Approaches Basin to the east and the Mauchline Basin in Ayrshire to the west, suggests that the region could have once had significant Permian and Jurassic sediment cover (Underhill et al, 2008 and Vincent et al, 2010). Results of fission track analysis (unpublished) from the 25/26-1 well give evidence of >1.3 km of now eroded sedimentary cover (Underhill et al, 2008). It is thought that deposition ceased in the early Palaeogene with start of uplift, magmatism and erosion related to the opening of the North Atlantic (Vincent et al, 2010).

During the Quaternary, the area was overwhelmed by glaciers on more than one occasion, with resulting thick deposits of till (boulder clay) and glaciofluvial sands and gravels. Fluctuations in sea level due to climate change resulted in deposition of thick marine and estuarine clays during transgressions and, during marine regressions, permitted the emergence of beaches which are now located several metres above sea level.

2.2 Structure

2.2.1 Folding
The major structural element in this region is a syncline with an approximately north – south axis, commonly referred to in general accounts of the Midland Valley as the Central Coalfield Syncline. Locally, the structure is referred to as the Clackmannan Syncline in the district north of the River Forth, and the Falkirk-Stane Syncline to the south of the river.

The syncline is asymmetrical, with average dip on the eastern limb up to 30°, but in the west dip rarely exceed 5°. The syncline closes to the south (i.e. plunges north) with very low northerly dips on the axis.

In the north, the syncline axis is almost coincident with the deepest part of the Kincardine depositional basin, and the terms Kincardine Basin and Clackmannan Syncline are often used interchangeably. The depocentre of the Kincardine Basin actually lies some 2-3km east of the
syncline axis within the AOI and also extends southwards towards Falkirk but terminates against the Banknock/ Mungal Fault Complex.

Minor anticlinal folds are superimposed on this dominant syncline structure and are known at outcrop or from shallow mining – it is not known whether they continue to any great depth. Within the AOI, the Culross Anticline and Syncline outcrop on either side of the Kincardine Ferry Fault, with steep dips across the fold pair of 20° to 30°. The fold axes are about 1km apart and plunge at a low angle to the SW. The Culross Anticline can be traced northeast from its exposure on the coast until it converges with the Kilbagie Anticline. The Kilbagie Anticline extends eastwards from just south of Blairhall Colliery to the River Forth at Inch of Ferryton. No details have been published for it.

2.2.2 Faulting

The easterly trending Ochil Fault is the largest fault in the region, with the Kincardine Basin and Clackmannan Syncline terminating abruptly against its southern side. The southerly downthrow of the Ochil Fault is at its maximum near Alva, where high Middle Coal Measures have been brought against Lower Devonian lavas. An approximate figure for its throw is of the order of 3000 m (Francis et al, 1970). Most of this displacement is attributable to Devonian and Carboniferous movement, and it has been suggested that during the Carboniferous, the Ochil Fault separated an area of relatively slow and intermittent subsidence to the north from the rapidly subsiding Kincardine Basin to the south. At outcrop, the Ochil Fault is seen to be inclined to the south with a hade of 63° to 72°.

At outcrop, the fault zone is often intruded and deformed by pods of quartz dolerite and is associated with a ‘wide’ belt of complex faulting and synclinal folding in Coal Measures (Francis et al, 1970) possibly relating to fault drag. Seismic evidence (the fault is still active) indicates that it might be a reverse fault and is inclined to the north at depth.

South of the Ochil Fault and within the AOI, most of the normal faults fall into three groups, with easterly, northeasterly, and northwesterly trend:

- **Easterly Faults** - these are the most numerous fractures and are possibly related to movement on the Ochil Fault. Within 6.5 km of the Ochil Fault the majority throw down to the south, from which point to Falkirk the dominant throw is to the north. However, south of Falkirk, the throw on the easterly faults can be either to the north or south. A group of easterly faults including the Banknock Fault, the Dennyloanhead Fault and the Mungal Fault form an important fault complex. Namurian strata dip away from the complex to the north and south, and higher Westphalian strata are preserved downthrown within the complex. The net throw across the zone at the western edge of the Clackmannan Syncline is down to the south, but in the east around Grangemouth the throw is down to the north. The change in sense of throw along the fault may indicate a component of lateral displacement. Within CNR’s Kincardine licence the remaining easterly faults as mapped at surface appear to define a terraced horst structure beneath the Forth. Faults occurring on the south side of the river throw down to the south (e.g. North Broomage, Orchard and Kinnaird House faults), whilst those on the north side throw down to the north (Kincardine Ferry and Sands faults). Mining data indicates that there are one or two instances of minor reverse displacement on the easterly faults (e.g. a reverse throw of about 15 m occurs on a fault north of Bo’ness close to the projected line of the Mungal Fault). Several of the easterly faults south of the Mungal Fault complex and one north of the fault are intruded with quartz-dolerite dykes.
Northeasterly Faults – these faults, of which the Carnock Fault has the largest throw (290 m), are possibly structural adjustments related to movements along the Campsie Fault which terminates at the western edge of the Clackmannan Syncline. Most of the northeasterly faults throw down to the southeast.

Northwesterly Faults - these are mostly small in length and throw, but include two major branches from the Ochil Fault, the Sheardale Fault and Arndean Fault, the latter having a throw of several thousand feet. Northwesterly faults become increasingly common in the southern part of the Clackmannan Syncline where they often terminate against easterly faults. In several places, mine abandonment plans show easterly faults curving round without a break to take up a northwesterly alignment.

2.3 Lithostratigraphy

All stages of the carboniferous are stratigraphically represented within the MVS (Figure 2.2) and, with the exception of the Upper Coal Measures, are present at outcrop or at depth within the AOI (Figure 2.3). They are described in the following sections in reverse stratigraphical order. The extra-basinal sediment source for the MVS was predominantly the erosion of the Caledonian Mountains to the north and north east with some additional sediment supply from the south into the south of the basin (Browne et al, 1999).

A complete and comprehensive understanding of the stratigraphic variations in lithology is key in the development of a UCG project. This understanding must also encompass strata that may not be immediately vertically adjacent to target coal seams. Full descriptions of lithologies are provided in Geological and Economic Memoirs for this area (Cameron et al 1998, Carruthers and Dinham 1917, Clough et al 1920, Dinham and Haldane 1932, Francis et al 1970, Forsyth et al 1996, Haldane and Allan 1931, Hinxman et al 1917 and Read 1959) and details specific to particular locations may be found in boring records for water, coal and hydrocarbons. A summary of these data for specific stratigraphic intervals is provided in the following sections.

2.3.1 Middle and Lower Coal Measures (Westphalian, Upper Carboniferous)

These sub-units outcrop extensively in the core of the Clackmannan Syncline along the entire extent of its axis.

They consist of repeated sequences of grey to black mudstones and siltstones passing up into off-white, grey and brown, fine- to medium-grained sandstones which in turn underlie mudstone, siltstone, seatearth and coal.

This coal-cyclic, upward-coarsening style of sequence is of delta and alluvial plain origin, and includes facies associations typical of forest, shallow lake and sea, prograding delta, delta distributory channel, river channel, and floodplain environments.

There are many coal seams exceeding 0.3 m in thickness. At their thickest (square NS89SE), the preserved sequence of both sub-units combined is approximately 320 m.

The sub-units become slightly attenuated towards the north and less so towards the south. The base of the Lower Coal Measures (approximately base Westphalian A) cannot be defined accurately in Scotland due to paucity of fossils and is usually taken at the base of the lowest convenient mappable horizon – the Lowstone Marine Band in the Clackmannan Syncline.
Figure 2.2. Choristratigraphic and lithostratigraphic classification of the Carboniferous in the Midland Valley of Scotland.
2.3.2 Passage Formation (Namurian, Upper Carboniferous)

In its upper two thirds, this unit is dominated by white or off-white and reddish-brown, fine- to coarse-grained sandstones with some quartz-pebble conglomerates, interbedded with structureless mudstone in shades of reddish-brown (occasionally purple and grey). Coal seams underlie many of the mudstones but are thin and impersistent – the Bowhousebog Coal and Netherwood Coal may be useful marker horizons locally. The sandstones are upward fining and are mainly sub-arkoses (quartz arenites and sub-litharenites also occur) occurring in beds up to 24 m thick (commonly <12 m).

The coal seams are, with local exceptions, thin and do not show good continuity laterally but there are a number of marine bands that do enable correlation between boreholes (Cameron et al, 1998).

The lower part of the formation closely resembles that of the underlying Upper Limestone Formation. It includes up to three thin marine limestones or fossiliferous mudstones with sandstones and thick unbedded mudstones. The Roman Cement Limestone and overlying shelly mudstone (No 2 Marine Band) is a consistently developed marker horizon throughout the region. Pink and variegated fireclays (the Lower Fireclays) are another notable feature of the lower part of the Passage Formation.

The upper part of the Passage Formation is mainly fluvial in origin with the sandstones being deposited by braided, low sinuosity and meandering rivers on an extensive alluvial plain. Short-lived marine transgressions are indicated by the many thin marine band mudstones. The lower part of the

Figure 2.3. Outcrop geology map for the AOI.
formation is also predominantly fluvial, but displays an increased influence of shallow marine incursions.

The base of the Passage formation is normally defined by the top of the Castlecary Limestone in the MVS. However, in this area, the Castlecary Limestone has been removed by a minor unconformity, and the base of the Passage Formation is often difficult to define.

The passage formation varies considerably in thickness throughout the Clackmannan Syncline, being thickest at Kincardine (340 m) and thinning in all directions.

2.3.3 Upper Limestone Formation (Namurian, Upper Carboniferous)
This formation consists of long upward coarsening sequences of grey to black mudstone, overlain by siltstone and off-white to brown, fine- to medium-grained sandstone, capped by seatearth, limestone and occasionally coal. The coals are usually less than 0.6 m thick, with one exception, the Upper Hirst Coal, which is consistently thick and can attain up to 2.56 m in northern parts of the Clackmannan Coalfield.

The main environments represented are deltaic and shallow water marine shelf. The presence of fossil soil horizons and coal show that delta top and delta plain environments existed. Burrowed horizons indicate that delta lobe abandonment with subsequent marine reworking of the delta top was a frequent occurrence.

Basalt and volcanogenic sediments such as waterlain tuff and tuffaceous siltstone occur at several levels in the formation. These beds are 3-60 m thick around Kincardine and the area of the Clackmannan Coalfield lying to the south. Basalt lava flows occur in the south and replace most of the sedimentary succession either just above or below the Calmy Limestone. These rocks belong to the Bathgate Hills Volcanic Formation, described in Section 2.2.9.

The top of the formation is defined by the top of the Castlecary Limestone (often removed Clackmannan Coalfield by a minor unconformity at the base of the Passage Formation) and the base is defined by the base of the Index Limestone (usually less than 1 m thick and overlain by a thick unit of dark grey mudstone). Several distinctive and consistent marker horizons are present in the sequence including the Bishopbriggs Sandstone, Cowie Rock, and Cadgers Loan Sandstone in the lower part, and the Lower Hirst Coal, Upper Hirst Coal, Calmy Limestone, and Plean No 1 Coal in the upper part.

In the Clackmannan Coalfield, the Upper Limestone Formation shows a significant thickening north of the Banknock/Mungal Fault complex. A maximum thickness of 470 m is recorded near Alloa and extending north and northeast to Dollar. It thins to around 200 m to the south of the River Forth.

2.3.4 Limestone Coal Formation (Namurian, Upper Carboniferous)
The top of the formation is picked at the base of the Index Limestone and the base is defined as the top of the Top Hosie Limestone. The formation outcrops extensively in the Kincardine district and beneath the Firth of Forth.

This unit consists of repeated short sequences of black or grey mudstone passing upwards into siltstone or laminated silty mudstone and sandstone which are overlain in turn by seatearth and thick coal. Often, the cycles are incomplete, with one or more of the component lithologies absent,
making local correlation difficult, especially in the upper part of the sequence where variability is most pronounced.

The sandstones are generally fine- to medium-grained and off-white or buff in colour. Thick (7.5-30 m) channel sandstones are present which have sharp erosive bases and become finer grained upwards. Beds of ironstone, both clayband and blackband (clayband interleaved with coal) are common in the east-central and northeastern parts of the licence. A single, thin, freshwater limestone (the Berryhills Limestone) is intermittently present near the top of the formation.

Strata with a marine fauna occur within the lower part of the formation in the Johnstone Shell Bed and the Black Metals, and become more prevalent towards the west. This fossiliferous rock is dark grey or black, slightly calcareous mudstone usually with thin clayband ironstone beds and nodules. The Black Metals is an unusually thick and persistent bed of dark grey bituminous shaly mudstone.

The environments of deposition were lacustrine deltaic in the upper part, marine deltaic in the lower part, with the upward coarsening sequences (mudstone to sandstone) representing prograding delta lobes. Thinner upward fining sequences represent river channel and alluvial or deltaic floodplain, and swamps are represented by plant-bearing mudstone, seatearth and coal.

Swamp conditions are thought to have been more prevalent in the east of the Clackmannan Syncline, as total thickness of coal within the succession increases uniformly in this direction, as does the total thickness of the formation itself (see Figure 2.4). This easterly increase in coal development in the Kincardine area involves the appearance of many new coal seams towards the east, and a change in character (including splitting) of existing seams when traced eastwards. CNR’s UCG licence lies at an important transition point between the Limestone Coal Formation sequences of the Clackmannan Coalfield and the Dunfermline Coalfield. The resulting difficulties of seam correlation between different locations within the AOI are exacerbated by differences in seam nomenclature in historical accounts for different mining areas, and occasional seam misidentification at individual mines.
Figure 2.4 Comparative vertical sections of the Limestone Coal Formation through deepest part of the Kincardine Basin (adapted from Francis et al [1970]).

Table 2.1 contains a provisional correlation table for Limestone Coal Formation coal seams and limestones throughout the AOI. Key to seam correlation is the Bannockburn Lower Main Coal of Stirlingshire which, together with the Black Metals marine band, appears to be consistently and thickly developed throughout the district (except where replaced by extrusive volcanics south of the River Forth). In historical mining accounts for the Kincardine district, there is a tendency to discuss coal seams in three main groups (in downward sequence: Blairhall Group; Main Group; and Dunfermline Group).

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<td>Limestone</td>
<td>Index</td>
<td>Upper Limestone Fm</td>
</tr>
<tr>
<td>Coal</td>
<td>Blairhall Main, Bo’ness Splint</td>
<td>Limestone Coal Fm</td>
</tr>
<tr>
<td>Limestone</td>
<td>Berryhills</td>
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<tr>
<td>Coal</td>
<td>Hartley, Cowdenbeath Seven Foot, Upper Twenty Inch, Milton Main</td>
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<tr>
<td>Coal</td>
<td>Greenyards, Comrie Two Foot, Lower Twenty Inch</td>
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<tr>
<td>Coal</td>
<td>Bannockburn Upper Main, Bannockburn Steam, Auchenbowie, Upper Jersey, Diamond</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.1. Stratigraphically constant marker horizons are referred to by local names in driller’s journals, historical mining accounts and mine abandonment plans. This table lists the most constant seams throughout the AOI, and their synonyms.

Using the seam correlation and borehole records, it can be demonstrated that the thick coals familiar to coal mining in the Clackmannan Coalfield (the Main group comprising: the Knott; Bannockburn Lower Main; Bannockburn Upper Main; and Greenyards), can be easily traced northwards for several kilometres in the direction of Alloa, and have equally thick or thicker correlatives when traced eastwards and northeastwards towards Fife. A large variation in total coal thickness is apparent in the basin although, north of the Banknock/Mungal Fault complex at least, the percentage coal relative to other strata within the interval remains fairly constant. A general reduction in total coal thickness is observed towards the Ochil Fault. A marked increase in coal thickness towards east-central parts of the licence (corresponding to an overall thickening of the Limestone Coal Formation) is due to the development of a group of coals (the Blairhall group) between the Main group and the Index Limestone.

In the vicinity of Kincardine, there is an additional development of thick coal seams below the Black Metals in the Clackmannan Coalfield which is not present elsewhere (the Dunfermline group).

Contemporary volcanic activity is evident within the formation in the south of the AOI. In parts of the outcrop between Bathgate and Linlithgow, the entire formation is replaced by the basalt lavas and tuffs of the Bathgate Hills Volcanics (Section 2.2.9).

2.3.5 Lower Limestone Formation (Visean, Lower Carboniferous)
The Lower Limestone Formation outcrops beneath the Firth of Forth in the eastern part of the AOI and its likely presence at depth throughout the Clackmannan Syncline is known from limited drilling data. The absence of thick coals in this and underlying formations means that the top of the Lower Limestone Formation is effectively economic basement from a UCG standpoint.

The top of the formation is picked at the top of the Top Hosie Limestone and its base at the base of the Hurlet Limestone. The top of the formation also marks the top of the Lower Carboniferous (although the top Visean / base Namurian boundary actually lies just below the Top Hosie Limestone in the Midland Valley).

The formation generally comprises pale grey to dark grey marine bioclastic limestone, black to grey mudstone and siltstone, and pale grey to off-white fine- to medium-grained sandstone in long, coarsening upward cycles. It is not so readily divided into cycles of sedimentation as overlying formations due to a lack of coal seams and the occasional absence of limestone dividing each cycle. The proportion of sand to mud increases northeastwards towards Fife. Close to CNR’s licence,
hydrocarbon well Inch of Ferryton 1 encountered several coals of thickness less than 1 m. Minor lithologies present include cannel and blackband ironstone.

The most common sedimentary environment represented is that of a shallow-water marine shelf. However, lower coastal plain marine deltaic and fluvial environments are represented, as are upper coastal plain lacustrine deltas.

As with the overlying Upper Limestone and Limestone Coal formations, the Lower Limestone Formation is replaced by, or interbedded with volcanics in the Bo’ness – Slamannan area (see Section 2.2.9).

There is a similar thickening of the succession on the east limb of the Clackmannan Syncline as in the Limestone Coal Formation. Thickness reaches a maximum basinal development of 213 m in the Bo’ness area, within the AOI.

2.3.6 Strathclyde Group (Visean, Lower Carboniferous)

The top of the Strathclyde Group is defined by the base of the Hurlet Limestone. The base of the group is defined by the base of the Clyde Plateau basalt lavas where present, and is undefined elsewhere.

To the west of Kincardine, the Strathclyde Group includes (in descending stratigraphical order): the Lawmuir Formation; the Kirkwood Formation; and the Clyde Plateau Volcanic Formation. In Fife and West Lothian, immediately east of Kincardine, the Lawmuir and Kirkwood Formations are replaced entirely by the West Lothian Oil Shale Formation. The western limit of the West Lothian Oil Shale Formation therefore lies close beneath the CNR’s licence, but the boundary is undefined due to paucity of deep drilling in the north, and obscured by the presence of the Bathgate Hills volcanics to the south. Similarly, the eastern limit of the Clyde Plateau Volcanic Formation is not known, but has not been encountered in any drilling east of its extensive outcrop west and south of Stirling.

The Group does not outcrop anywhere on the licence or AOI and is poorly known from limited deep mining and drilling. At outcrop, just west of Stirling, sediments of the Strathclyde Group (which do not include oil shales), rest on Clyde Plateau Lavas and increase dramatically in thickness on the downthrow side of the Campsie Fault near Denny. This rapid thickening suggests that fault-controlled differential subsidence along fractures with easterly or northeasterly trend may have influenced deposition at this time.

20km south of the AOI, the Salsburgh 1A gas well encountered a thick (576 m) sequence of Strathclyde Group sediments assigned to the West Lothian Oil Shale Formation. The sequence primarily consists of black to grey mudstone and siltstone. Bioclastic marine limestone and dolomite occur as thin beds within the mudstones. Rare, thin non-marine limestones are also interbedded. Off-white to grey, fine- to medium-grained, occasionally coarse and pebbly sandstone is generally subordinate, occasionally arranged in upward fining multi-channel units. Seatearth, thin coals, blackband and clayband ironstones, bituminous mudstones and oils shales also occur. This sedimentary sequence rests above the Salsburgh Volcanic Formation, whose relationship to the possibly contemporary Clyde Plateau lavas has not been established.
The Geological Survey borehole at Rashiehill, 20 km south and west of the AOI, showed the Strathclyde Group to be represented entirely by volcanic rocks (Bathgate Hills volcanics overlying Clyde Plateau lavas).

In the Inch of Ferryton 1 well, close to the western edge of the AOI, the upper part of the Strathclyde Group is faulted out or missing by non-deposition. What remains (140 m thick) consists of finely interbedded light grey, fine-grained sandstone, grading to slightly calcareous siltstone and dark grey to brown, slightly calcareous and micaceous mudstone with traces of ironstone. There are relatively thin bands of light grey to light green volcanic tuff. Rare limestones were seen in the upper parts, below which thin coals, characteristic of the Lawmuir Formation at outcrop to the west, were recorded in an interbedded sandstone/mudstone sequence. No oil shales were recorded, but would most likely exist in the missing upper section.

Within the AOI, at Kinneil Colliery, Shafts 1 and 2 proved the uppermost strata of the West Lothian Oil Shale Formation, down to the Raeburn Shale. The proven succession appears to be thin (118 m) compared to that only a few kilometres to the east. The interval between the top of the Raeburn Shale and the base of the Hurlet Limestone is composed largely of argillaceous rocks and thin coal seams. Sandstone is uncommon, and only one bed exceeds 6 m thick. One limestone and three marine mudstones are recorded. The Raeburn Shale itself is at least 15 m thick with burnt vestiges of shells above a thick 10+ m quartz-dolerite sill in which both shafts terminate.

2.3.7 Inverclyde Group (Tournaisian, Lower Carboniferous)

49 m of Tournaisian age strata were identified in hydrocarbon exploration well Inch of Ferryton 1. These rocks occur at the very base of the Lower Carboniferous and rest directly on Devonian strata. The top of the Group is marked by an unconformity.

In the well, the unit is mainly composed of fine- to medium-grained, light grey to light green sandstone with occasional tinges of red. It is slightly calcareous and argillaceous in places, with thin interbeds of red-brown, soft mudstone. Occasional thin bands of tuff are also seen. Petrographic studies show that the sandstones are less mature than those of the overlying Strathclyde Group.

During deposition of the group, the axial flow in the MVS was from the southwest and marine faunas are rare but present (Browne et al, 1999).

2.3.8 Upper Devonian

Well Inch of Ferryton 1 penetrated nearly 1500ft of Upper Devonian sediments (Stratheden Group).

The uppermost 85 m of the unit was marked by an abrupt change from the overlying sandy section to a monotonous unit of soft, sticky mudstone which is generally red-brown, but occasionally purple or light grey. It is silty in places with some loose medium-sized, well-rounded sand grains and traces of blue-grey, blue-green and white volcanic tuff/ash.

The remainder of the sequence is predominantly a breccia conglomerate, comprising varicoloured volcanic fragments in a matrix of, and occasionally interbedded with, soft silty, red-brown mudstones with occasional red-brown siltstones and loose, medium to coarse grains of sand.
2.3.9 Volcanic Rocks

2.3.9.1 Extrusive Volcanic Rocks
The Bathgate Hills Volcanic Formation represents a persistent and widespread phase of volcanic activity lying immediately to the south of the AOI. Pyroclastic rocks and basalt lavas resulting from this vulcanicity are first recorded in strata at the top of the Strathclyde Group and continue to interfinger with, or entirely replace, sediments of all overlying formations up to, and including the lower part of the Passage Formation. The rocks are seen at outcrop in the Bathgate Hills on the eastern limb of the Clackmannan Syncline, and are known to extend westwards beneath younger strata.

The lateral distribution of the formation, and extent to which clastic coal-cyclic sediments are replaced by them within the southern part of the AOI is highly conjectural due to paucity of deep drilling. However, the volcanic rocks appear to have a maximum aggregate thickness at outcrop of 600 m just south of Linlithgow. Westwards from here, drilling and mining data in the Upper Limestone Formation suggests that the volcanics are restricted to a subcircular area, 20 to 25km in diameter, emanating from volcanic centres close to the Redding and Couston.

At Kinneil Colliery, within the AOI, volcanic and volcanlastic rocks of the Bathgate Hills Volcanic Formation are present at several levels within the mined Limestone Coal Formation sequence and the negative impact on the coal resource in that area is significant. Due to a lack of deep drilling data, there is great uncertainty as to how far the replacement of coal-bearing sediments by volcanics extends northwards beneath the Firth of Forth at Kinneil in CNR’s licence.

2.3.9.2 Vents and Plugs
A number of volcanic vents are mapped at outcrop in Upper Limestone Formation strata in and close to the northern boundary of the AOI (Figure 2.3). Thick veins of tuff and olivine basalt recorded in the Limestone Coal Formation in Blair Mains 2 bore are attributed to the close proximity of a volcanic neck. Other underground occurrences of tuffs in the Bogside Mines and Bogside Colliery 4 bore, within Upper Limestone Formation strata, are also interpreted as volcanic necks concealed beneath younger strata.

2.3.9.3 Intrusive Volcanic Rocks
A quartz-dolerite sill, known as the Midland Valley Sill, is the most significant intrusive igneous body in the region. Its outcrop within the Clackmannan Syncline is imperfectly annular and dips inward from both limbs towards the syncline’s axis.

In the north of syncline, the sill is largely contained within the Lower Limestone Formation and lower part of the Limestone Coal Formation, changing from one horizon to another along dyke-like risers. Its position in the sequence is thought to be highest close to, and north of, the Abbey Craig Fault where Main Group coals of the Limestone Coal Formation as high as the Hartley have been anthracitised, burnt and completely replaced in workings at Polmaise and Manor Powis collieries north of Stirling. Towards the axis of the syncline, north of the River Forth near Alloa, it is recorded in bores at levels just below the Black Metals in the Limestone Coal Formation (e.g. Inch of Ferryton 1, where it is 156 m thick, and Polmaise Colliery 4, where 92 m was recorded).
Its position east of the syncline axis north of the River Forth is less well known – it is not present immediately below the Black Metals in bores north of the Clackmannan Fault and its easterly extension into Fife. It does, however, reappear at outcrop on the eastern flanks of the syncline, well to the east of the AOI, at a much lower stratigraphic position within the Strathclyde Group (Lower Carboniferous). In Composite Energy’s Longannet 1 CBM well, 25 m of dolerite was encountered at 1091 m MD at a level within the middle of the Dunfermline group of coals below the Black Metals Marine Band and no doubt replaces some of the Dunfermline group coals at that location. To the South of the Clackmannan Fault in the vicinity of Culross, Valleyfield and Blairhall, the sill is recorded in various mines and bores stepping through strata in the vicinity of the Black Metals, but is much thinner (38-73 m) than to the west, and does not appear at this level at outcrop south of the Clackmannan Fault, a short distance to the east. At some locations (e.g. Culross 1 borehole), the sill has destroyed or affected potential UCG target coals in the Main group (see Figure 2.5).

The sill has not been detected in deep drilling penetrating close to the top of the Lower Limestone Formation south of the River Forth at Airth (e.g. Airth 6) or at Orchardhead F northwest of Grangemouth, and is therefore assumed to occupy a position within the Lower Carboniferous here.

In west Fife, in the area between Parklands 1 and Solsgirth 1 bores, and stretching south through Blairhall Colliery and to the River Forth, a techenite and basanite sill steps through various horizons in the Limestone Coal Formation and Upper Limesstone Formation. This sill is 35 to 49 m thick in the Valleyfield, Blairhall and Comrie Collieries and has a complex relationship with the Midland Valley dolerite sill (see Figure 2.5).

For both quartz-dolerite and techenite/basanite sills, where they have been intruded into Limestone Coal Formation strata, the country rock is altered in the vicinity of the intrusion. Coals are often burnt or anthracitized, and there are also distinct zones of ‘white trap’ – zones of hydrothermal alteration associated with faulting and mineralization (including calcite, pyrite, barite, and occasionally chalcopyrite) commonly accompanied by impregnation of hydrocarbons. The alteration has possibly been produced by volatiles released during distillation of oil shales by the heat of the intrusion.
Figure 2.5. Ribbon diagram illustrating complex relationships of the Midland Valley dolerite sill, and the Fife teschenite sill to the coals of the Limestone Coal Formation. From Francis et al (1970).

2.4 Subsurface Temperature

The Scottish Midland Valley has been the subject of two Geological Survey investigations into geothermal energy potential. All available temperature measurements at the time of publication (mid 1980s) were assessed in order to determine the temperature at which formation fluids might be found at depth. The estimates were carried out using selected borehole temperature measurements for each of the major stratigraphic formations penetrated. From this data, thermal gradients over particular stratigraphic intervals were established, enabling interpolation and extrapolation of temperatures to be carried out for intervals where no direct temperature measurements were available at a particular location.

For the area of the Clackmannan Coalfield, the resulting contoured temperature estimates at the base of the Limestone Coal Formation are presented in Figure 2.6. The temperature distribution indicates the presence of a geothermal ‘hotspot’ that is more or less coincident with the deepest parts of the Clackmannan Syncline beneath, and to the north of, the Firth of Forth. Warmest
formation temperatures are predicted for the Longannet Point and also south of Alva, where temperatures at the base of the Limestone Coal Formation may be slightly in excess of 50°C (122°F).

Figure 2.6. Temperature at top of the Lower Carboniferous (Browne et al, 1985).

Since the mid 1980s, little new information has become available from deep drilling in the Clackmannan Syncline. Data from Inch of Ferryton 1, drilled by Tricentrol Exploration in 1986, has been released providing temperature data from one Selective Formation Tester (SFT) run. The SFT tool was run over a 1050ft interval in the upper part of the Limestone Coal Formation and interpretation of the published data suggests a temperature gradient of 21.9°C/km. Temperatures recorded just above and below the interval containing the Greenyards, Upper Main, Lower Main and Knott coals were 38.1°C (100.6°F) and 40.7°C (105.2°F) respectively, with an interpolated temperature at the position of the Bannockburn Lower Main Coal of 39.5°C (103.1°F). An extrapolated temperature estimate for the base of the Limestone Coal Formation is 49.2°C (120.6°C), consistent with Geological Survey predictions.

A temperature and conductivity survey was performed at Composite Energy’s Airth 6 CBM exploration well in 2005. An overall average temperature gradient of 18.5°C/km was observed in the logged section of the well (water level at near top Passage Formation to top Black Metals), slightly
lower than most Upper Carboniferous gradients published by Geological Survey. However, there was a noticeable increase in gradient for the section below the Index Limestone for which a local gradient of 28°C/km applies. At the Bannockburn Lower Main Coal, a temperature of 29.2°C (84.6°F) was recorded. An extrapolated temperature for the base of the Limestone Coal Formation at Airth 6 using the higher gradient for the Limestone Coal Formation is 36°C (97°F), which is consistent with Geological Survey predictions for this location. An influx of warm (63°C [145°F]) fresh water into the well from a 3ft zone near the top of the Limestone Coal Formation may account for the anomalously low gradient above this point in the well.
3 History of Mineral Exploitation

3.1 Coal Mining
Coal mining has had a major impact on the central belt of Scotland. During its peak in the early 20th century it is estimated that nearly 150,000 people were directly employed by Scotland’s mining industry. At point of nationalisation in 1946 there were 300 mines operating in Scotland, this number declined quickly to 30 by 1980 and presently there is no deep coal mine remaining in production in Scotland.

More than 36 coal seams are known to have been worked in the project AOI and surrounding area involving many hundreds of mine entries. The project area lies at the intersection of the Clackmannan and Dunfermline Coalfields each with similar but distinct coal-bearing sequences at each stratigraphic level. This is reflected by considerable confusion in the different naming of coal seams. The final deep-coal workings in the AOI (and in Scotland) halted in 2001 at Longannet Colliery after a major influx of water from adjacent (abandoned) workings made the mine unworkable.

3.1.1 Coal Measures
The thick coals of the Lower and Middle Coal Measures contained in the core of the Clackmannan Syncline have been worked at outcrop and underground since the Middle Ages. Opportunities may still exist for small-scale opencast working but, for the purposes of this report, the resource is considered to have been exhausted.

Uncharted mine entries and abandoned workings in multiple seams of coal and associated minerals within the Coal Measures should be anticipated wherever they outcrop in the AOI. Shallow voids, loosely compacted mine waste, and weak roof-supporting pillars within abandoned workings pose a high risk of rockhead and surface instability and loss of fluid circulation at drilling locations.

3.1.2 Passage Formation
The most valuable mineral deposit within the Passage Formation has been the fireclays in its lower part (the Lower Fireclays) – underground workings are known to extend from outcrop on the western limb of the Clackmannan Syncline at Dunmore, Torwood and Bonnybridge. On the eastern limb of the syncline, the only known underground workings are at Birkhill, 3km southeast of Grangemouth and therefore outside of the AOI.

The Bowhousebog Coal, in the upper part of the Passage Formation locally attains a thickness of 1.3 m between Larbert and Dunmore and several old pits are believed to have worked it at both locations and in the intervening ground.

Abandoned mine workings therefore pose a risk to surface stability and loss of circulation at drilling locations wherever the lower part of the Passage Formation subcrops beneath superfronts, and close to the outcrop of the Bowhousebog Coal.

3.1.3 Upper Limestone Formation
Except for the Quarry Coal, which was worked underground on a small scale at Fallin (Polmaise No 3 Pit) and Cowie (Bannockburn Nos 1 and 2 Pits amongst others), the Lower and Upper Hirst Coals are the only seams in the Upper Limestone Formation that have been mined. Both of these areas of
underground working are on the western limb of the Clackmannan Syncline and distant from the AOI.

The Upper Hirst Coal has been worked on a small scale beneath the AOI and indeed CNR’s licence on the eastern limb of the Clackmannan Syncline since the 13th Century. Most notable (and probably extensive) were underground workings from (amongst other locations) the Moat Pit on a tidal island on the River Forth, which opened in 1590 (Figures 3.1 and 3.2).

Figure 3.1. 1:10560 scale Geological Survey map (dated 1921) showing location of the 16th Century Moat Pit relative to the outcrop of the Jenny Pate (== Upper Hirst) Coal. Also shown is the location of the slightly earlier Castlehill Pit.
The earliest known workings in the Hirst coals on the western limb of the Clackmannan Syncline are at Cowie, where pits dating from 1873 worked the coals over a limited area (3 acres) from 1873 to 1879. The Upper Hirst was again worked at nearby Bannockburn Nos 1 and 2 Mines from the early 1950s to the early 1960s. Other collieries working the Hirst in the early 1950s were Manor Powis and Herbertshire. All of these locations are distant from the AOI.

During the early 1960s, the requirements of the Kincardine coal-fired power station on the axis of the Clackmannan Syncline saw the opening of several new mines working the Upper Hirst Coal. New drift mines opened at Dollar and Bogside to the north and northwest of the AOI, and the existing operation at Polmaise Colliery (far to the west, near Stirling) was extended to include the Upper Hirst. The mines at Bogside and Dollar had periods of extreme difficulty due to unexpected faulting, excessive water and igneous intrusions.

The opening of a new coal-fired power station at Longannet (Figure 3.3) in the mid 1960s (within the AOI) also saw the opening of new drift mines to the Upper Hirst on the site and in its vicinity forming a huge interconnect network of mines stretching between the River Forth and the Ochil Fault. The mine at Castlehill extended workings from the Bogside Colliery and new drift mines were opened at Solsgirth and Castlebridge. Longwall working was the preferred technique employed in the Longannet Complex of mines.
Figure 3.3. Oblique aerial photograph of Longannet Mine. The photograph was taken in 2006, five years after the mine closed following a flooding incident. The inclined mine entry is located amongst the building near the top of the site. Image copyright RCAHMS (Collection Nr: DP017134).

No known workings in the Hirst Coals exist south of those at Cowie, on the southern side of the Firth of Forth and western limb of the Clackmannan Syncline. Immediately to the south of the AOI (south of the Banknock/Mungal Fault Complex) mining accounts describe the Hirst as being represented by one or two thin (0.33-0.83ft) seams of no economic value. This implies an abrupt and widespread thinning of this coal south of Grangemouth.

The preferred method of longwall extraction in the Hirst means that surface instability over sites of known working is unlikely. However partially collapsed Hirst workings and uncollapsed roadways do pose a significant risk to lost circulation at drilling locations above them.

3.1.4 Limestone Coal Formation

Volumetrically, the most significant extraction of coal resource in the region has taken place within the Namurian coals of the Limestone Coal Formation. As previously mentioned, these coals increase in number and thickness within the Clackmannan Coalfield in an eastwards direction towards the Dunfermline Coalfield. CNR’s AOI is located on the cusp of these two fields and therefore exhibits a hybrid sequence of coal inheriting characteristics of both fields.

Small-scale underground mining to the Limestone Coal Formation coals on the eastern limb of the Clackmannan Syncline probably began in the late 18th and early 19th Centuries just to the east of
Culross Village by the Dundonald estates. This was the westwards (down dip) progression of extensive workings from outcrop in the Dunfermline Coalfield. Three pits were sunk in the latter part of the 18th Century in the tidal part of the Forth estuary at Preston Island (Figure 3.4). These pits worked nine coal seams in the Limestone Coal Formation of which three are recorded as attaining gross thickness of >1.8 m (Milton Main Coal [1.83 m] and Diamond Coal [2.74 m]). The Preston Island pits closed after a catastrophic methane explosion in 1811 before the legal requirement to submit plans of the abandoned workings.

Figure 3.4. Oblique aerial photograph of Preston Island taken in 1988. Image copyright RCAHMS (Collections Item Nr: SC1156835).

Large-scale deep mining had spread down dip towards the Kincardine licence from the Dunfermline Coalfield by the mid 19th Century. Two large collieries opened at Comrie and Blairhall at this time. Workings from these pits were extensive in the down dip direction within and just to the north of the AOI. It is known that a characteristic of the Comrie Three Foot Coal (== Greenyards Coal further
west) worked in the Comrie Mine was that it gave off a considerable amount of gas that hampered cutting and blasting.

Central to the AOI, the Valleyfield Colliery (Figure 3.5) opened in 1873 amongst the vestiges of earlier 18th Century workings and remained the largest location of extraction for Limestone Coal Formation coals north of the Forth until its closure in 1978. Many seams were extensively worked westwards beneath Culross, and southwards beneath the Firth of Forth towards Kinneil Colliery with which it was eventually linked by a tunnel.

Figure 3.5. Oblique aerial photograph of Valleyfield Colliery dating from 1928. Image copyright RCAHMS (Collections Item Nr: SC1259344).

South of the Forth, shaft sinking began at Kinneil Colliery in the 1800s (Figure 3.6), but earlier shafts are known to the east at Bo’ness. Many seams were worked at Kinneil but the principal coal wrought was the Seven Foot Coal (== Hartley Coal). In 1964 Valleyfield and Kinneil Collieries were linked by a tunnel running under the Firth of Forth. Kinneil finally closed in 1983 after many disappointing years in difficult mining conditions (primarily relating to faulting).
No Limestone Coal Formation workings are known within the AOI immediately south of Kinneil Colliery on the eastern limb of the syncline where the Bathgate Hills Volcanic Formation largely replaces the coal-bearing strata of the Limestone Coal Formation at outcrop.

Figure 3.6. Photograph of Kinneil Colliery probably dating from the early 1950s. Image copyright AditNow (http://www.aditnow.co.uk/).

3.2 Hydrocarbon Exploration and Production
The Midland Valley of Scotland (MVS) is proven hydrocarbon province and has a long history of production. It was the location of the first commercial hydrocarbon production in the UK through development of the distillation of ‘Boghead Coal’ (torbanite of Dinantian age) to oil. This process began in the mid 19th century and was carried out until the source was exhausted. After this, attention was directed towards the similarly aged but less productive ‘West-Lothian Oil Shales’ which were produced, through destructive distillation, from around 1878 initially at West Calder. The production from oil shales in this region peaked during the First World War at around 2.1 million barrels per year but production slowly declined until 1964 when tax concessions were removed and production ceased. It has, since then, been estimated that around 75 million barrels of oil was ultimately produced and around 37 million barrels may remain recoverable (DECC, 2010).

Conventional hydrocarbon exploration has had limited success within the MVS. The Midlothian oilfield produced just 30,000 barrels of oil during its 19 year of production (1946-1965) and the Cousland Gasfield produced 330 million cubic feet over a ten-year period (DECC, 2010). In more modern times, Burmah made an oil discovery at Milton of Balgonie in Fife and Marinex made a small gas discovery at Bargeddie, in the Upper Oil Shale Group in 1989. In the Firth of Forth (to the east of the AOI of this project) there has also been hydrocarbon exploration; Conoco drilled exploration well 25/26-1 (Firth of Forth-1) in 1990 which was plugged and abandoned with oil shows. The well
targeted a seismically-defined fault-related anticline at a depth of 2040 m. Close to the AOI’s northwestern corner, Tricentrol’s Inch of Ferryton 1 well reached Devonian with no shows in 1985 although significant gas kicks were recorded as each coal in the Limestone Coal and Lower Limestone Formations was penetrated. The strongest gas kicks were recorded in the deep coals of the Lower Limestone Formation.

Unconventional hydrocarbon exploration has dominantly focussed on coal-bed methane (CBM) in the MVS. Since the 1990s the potential for CBM development at Airth (on the western border of the AOI) has been investigated first by Hill Farm Coal Ltd (latterly CBM Ltd) who drilled and hydraulically fractured 5 wells in the period 1993-1997. Between 2004 and 2011, a further 10 wells were drilled by Composite Energy (six multilateral horizontal wells) for the Airth pilot production test and, on acquisition of the project by Dart Energy in 2011, two more multilateral production well were drilled at Airth. No detailed flow rates are available for this project and the field is currently shut-in pending a public inquiry following Dart’s submission of a full field CBM development.

Desorption/adsorption analysis of the Limestone Coal Formation coals at Airth have proved that seams at that location have high gas content and good methane saturations (pers comm David Goold, former Chief Geologist at Composite Energy Ltd). The Airth CBM pilot site lies on a possible lineation of methane outbursts and fatal mine explosions which extends from Kilsyth and Kirkintilloch (north of Glasgow) through Denny and East Plean then continues on the north side of the River Forth from Valleyfield Colliery and Preston Island to Oakley near Dunfermline. CNR’s UCG licence lies directly over this possible lineament of methane-saturated coal seams in the Limestone Coal Formation (Figure 3.7).
Figure 3.7. Map showing location of a lineament of fatal mine explosions in workings within Limestone Coal Formation seams in the Central and Clackmannan Coalfields. Data from UK Government statistics summarised by scottishmining.co.uk. Note that a break in the lineament occurs in the axis of the Clackmannan Coalfield where the seams were too deep to be mined but where high gas contents and saturations have reported to have been measured by Composite Energy in exploratory CBM drilling at Airth.
4 UCG Prospectivity

4.1 Criteria
At the most fundamental level, five primary criteria are taken into account when screening for UCG prospectivity:

- Net seam coal thickness (seams should contain \( \geq 1.8 \) m gross coal thickness with no more than three partings each \( \leq 20\% \) of the seam height);
- Seam quality (various parameters identified including: ash [density], sulphur and volatile matter content, maturity and calorific value);
- Structural compartmentalisation (sufficient continuous coal resource should be identified to deliver a volume equivalent to 1 MT suitable for a pilot test);
- Vertical and lateral separation from protected aquifers, potentially open fractures and mine workings (150 m in all directions); and
- The identified resource and any impact operations may have on adjacent strata must occur at depths from ground surface in excess of any constraint imposed by the licensing authority or other regulator (300 m).

4.2 Identification of Target Coals
The primary data sources used to identify target coals were; mine abandonment plans, borehole records, BGS Surface Geology maps and BGS memoires associated with these. The stratigraphic sections presented on the maps detail the coals found in the section along with their range in thickness. A database of coal depth and thickness was created using data from pits, shafts and hydrocarbon boreholes using publically available borehole records. Mine abandonment plans have depth and thickness data associated with worked seams along panels and along spine roadways, these were also integrated into this database. A significant difficulty with this selection process was the differing names given to coals mined in different part of the AOI. The correlation of coals from the north and south side of the River Forth is often uncertain and at times is contradictory from different data sources.

4.3 Coal Thickness
Figure 4.1 lists the main coals (and their thickness ranges) and other marker horizons identified in the licence area. The coals taken forward to be considered for UCG were primarily identified by thickness. The only coals in the licence area which potentially attain a cut-off thickness of 1.8m (~6ft) are (chronologically in oldest to youngest): Six Foot Coal, Blairhall Main Coal, Seven Foot Coal, Wester Main Coal and the Upper Hirst Coal. These coals are highlighted in red in the table below which lists most worked coals (along with some other important marker beds) found in the AOI. The only other coal of sufficient thickness listed (the McNeish Coal of the Middle Coal Measures) is not present in the licence area.
Figure 4.1. Stratigraphic column identifying persistent marker horizons and average coal thicknesses within the AOI. Where possible alternative local names for the same horizons are listed.

All of the target coals have been worked by traditional mining methods within the project AOI. All except the Upper Hirst have been worked in the east of the licence area where they are at shallower depths. The Upper Hirst seam conversely has been worked in the west – extensively onshore and to a lesser degree under the Firth of Forth (Figure 4.2).
Figure 4.2 Map showing distribution of charted underground workings in coal seams exceeding threshold gross and net thickness requirements.

In the next phase of thickness analysis, many thousands of xyz points were digitised from mine abandonment plan thickness measurements. Detailed thickness mapping of each of the target seams using this data revealed that only two of the five coal seams which are regularly reported to attain thicknesses of >=1.8m sustains this thickness over large parts of CNR’s licence; these are the Upper Hirst Coal and the Wester Main Coal. Figures 4.3 and 4.4 are thickness maps for the Upper Hirst and Wester Main coals respectively.
Finally, risk mapping of likelihood that each seam locally may not achieve the minimum thickness criterion (1.8 m) was carried out on the digitised thickness data for the Upper Hirst Coal and the Wester Main Coal (Figures 4.5 and 4.6 respectively).

**Figure 4.3.** Thickness distribution map for the Upper Hirst Coal.

**Figure 4.4.** Thickness distribution map for the Wester Main Coal.
Figure 4.5. Risk map for the the Upper Hirst Coal showing likelihood of the seam not achieving minimum threshold criteria.

Figure 4.6. Risk map for the the Wester Main Coal showing likelihood of the seam not achieving minimum threshold criteria.
4.4 Coal Quality

Coal quality data is available for four out of the five target coals from historical colliery records. Data for the Upper Hirst, Wester Main, Blairhall Main and Six Foot coals were provided by CNR. In terms of UCG prospectivity, all the seams have been attractive sources of energy for at least two centuries and meet quality criteria \textit{a priori}. The two most important quality factors are the calorific value and the density. The calorific value used in the dry air-free (DAF) value which has been converted from BTU/lb to J/Kg for resource calculations. The calorific value of samples of each of the target coals was plotted spatially to look for sweet spot trends but it was assessed that they did not vary geographically and could therefore not be mapped with any confidence. As a result, average values are used in the resource calculations (Table 4.1).

<table>
<thead>
<tr>
<th>Coal</th>
<th>Avg. DAF (BTU/lb)</th>
<th>DAF Range (BTU/lb)</th>
<th>Avg. Density (g/cm$^3$)</th>
<th>Density Range (g/cm$^3$)</th>
<th>Related Colliery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Hirst</td>
<td>14140</td>
<td>13730-14540</td>
<td>1.41</td>
<td>1.33-1.53</td>
<td>Bogside</td>
</tr>
<tr>
<td>Wester Main</td>
<td>14965</td>
<td>13240-15280</td>
<td>1.33</td>
<td>1.29-1.37</td>
<td>Valleyfield</td>
</tr>
<tr>
<td>Blairhall Main</td>
<td>14965</td>
<td>13960-15300</td>
<td>1.33</td>
<td>1.27-1.45*</td>
<td>Kinneil</td>
</tr>
<tr>
<td>Six Foot</td>
<td>15275</td>
<td>14880-15690</td>
<td>1.32</td>
<td>1.29-1.43</td>
<td>Kinneil/Valleyfield</td>
</tr>
</tbody>
</table>

*Excluding one reading that was assumed to be erroneous (3.9g/cm$^3$)

\textit{Table 4.1. Average calorific and density values for four target coal seams in the AOI.}

The calorific value of the coals shows an increasing trend with depth; this is likely due to higher coal maturity with increasing depth of burial. The density of the three deeper coals is very similar whereas the Upper Hirst has a notably higher average and is due to a well-established higher ash content in this seam.

Volatile matter is generally high though variable between sample locations in the same seam (20-43% dry ash-free); sulphur content is very low (commonly <2% air dried for the Limestone Coal Formation coals, <1% for the Upper Limestone Formation coals); and ash content is also low (<8% air dried for the Limestone Coal Formation coals, <23% air dried for the Upper Limestone Formation).

4.5 Structural Mapping of Coals

4.5.1 Methodology

Mapping of the coals is particularly important both for fault identification and for panel planning. The process of mapping the coals in this project was based around legacy 2D seismic data originally acquired for oil and gas exploration and planning for underground extraction of the Upper Hirst Coal from the Longannet mine complex (Figure 4.7). This seismic interpretation was supplemented and calibrated with the aid of borehole and mine abandonment plan data. SEG-Y data were acquired from both the UK Onshore Geophysical Library and the British Geological Survey.
Figure 4.7. 2D seismic coverage obtained and interpreted for this project.

A pre-interpretation review of the available seismic (130 km in total) revealed that despite its vintage (early 1980s) quality was reasonable and should improve significantly with modern reprocessing. Due to potential delays caused by heavy workloads in UK reprocessing contractors, a decision was made to perform a preliminary interpretation based on the original dataset. This was performed using DUG Insight software which is optimally featured for reviewing pre-stack data quality control as well as offering significant advantages for interpretation and calculating gross rock volumes.

However, despite the reasonable quality, the seismic lines are widely-spaced in relation to the structural complexity, so borehole tops, fault analyses and mine abandonment plans of Old Coal Workings (OWS) have been key to understanding the structure and filling some of the gaps between seismic lines. Without this supplementary data, seismic faults and the target continuous reflection event segments would almost certainly be mis-correlated. Even with the supplementary drilling and mining data, some areas are of the licence have too poor data coverage to make an unambiguous interpretation. Risk mapping has been used to identify such areas where further data acquisition might be appropriate.

After review for reprocessing, the seismic interpretation workflow was as follows:

- Data loading into DUG Insight of:
  - Legacy 2D seismic lines in SEG-Y format (unfiltered, TVFiltered, MIGrated stacks and Pre-stack data);
55 borehole locations with associated data (checkshots for one well and top depths for key horizons and stratigraphic markers – no VSPs are available and attempts to create a synthetic seismograms from Inch of Ferryton 1 logs proved low resolution);

- Preliminary seismic well ties created without issues (more can be done, and is indeed necessary, after the reprocessing work is carried out);
- Creation of preliminary velocity model for time-depth/depth-time conversion – more advanced model is required, however, using mapped formation tops from well/borehole control;
- Seismic event picking and mapping;
- Combining of horizon depth data digitised from abandoned mine working plans (in TVDSS) with seismic picks (TWT converted to TVDSS) in order to correct mis-picks and adjust the velocity model;
- Creation of interpolation maps for the combined seismic and abandoned mine workings and borehole data into prospect maps for each of the target horizons;
- Subtraction of the interpolated maps from input control data to summarise propagation errors.

4.5.2 Results of the Structural Interpretation

Seismic line TOC86M112_TV (Figure 4.8) is the longest line in the project and is axial to the River Forth including the dogleg offshore Grangemouth. This line has been check shot controlled with the Inch of Ferryton 1 well in the northwest corner of the AOI although the distance between the line and the well is fairly large (c.1500 m).

![Interpreted seismic line TOC86M112 showing (distant) offset boreholes and well tie (Inch of Ferryton 1)](image)

Figure 4.8. Interpreted seismic line TOC86M112 showing (distant) offset boreholes and well tie (Inch of Ferryton 1).

In the interpretation of this line, the Upper Hirst Coal is imaged as a negative event and the Orchard Limestone as a positive event. The Blairhall Main and Wester Main Coals are both imaged as negative events. Lack of synthetic seismogram and VSP data prevents naming of deeper events.
In general, and especially in the north and west, the geological structure offshore appears to be reasonably benign from well Inch of Ferryton 1 in the west through Longannet 1 and Orchardhead F bores and at Culross 4. Line 112 does pass through an east-west fault immediately north of Grangemouth Dock but, north of this fault, the strata are relatively unfaulted at 2D seismic resolution especially at the Limestone Coal Group level (apparently less so at Upper Hirst level). This statement must be taken in the context of often poor data coverage and within the fault resolving limits of 1980s 2D seismic.

As already stated, the south side of the Forth, adjacent to Grangemouth and Kinneil Colliery, seismic structure appears to be more complex with spectacular flower structures (upward-splaying faults) developing on the south side of what is probably a significant west-east trending fault about 800m north of Grangemouth Docks.

Dips are generally very low (average 2-5 degrees) but in the extreme east of CNR’s licence there is a sharp increase in dip as the formations rise to outcrop in the vicinity of Culross (where most of the target coals are heavily worked beneath the Firth of Forth) and adjacent landward areas (e.g. dip magnitude map for the Upper Hirst Coal, Figure 4.9).

![Seismic map showing dip magnitude in the Upper Hirst Coal. Note the rapid increase in dip on the east side of CNR’s licence where the seams rise more rapidly to outcrop.](image)

In the absence of denser seismic coverage, the dip magnitude mapping obtained by integrating xyz data from mine abandonment plans with seismic interpretation provides a useful indication for the location of major faults where data is available. A dip magnitude map has also been produced for the Wester Main Coal horizon (Figure 4.10). This appears to agree with an interpretation of line 112 that, at this level, the strata are relatively unaffected by major faulting to the north of Grangemouth Docks.
Docks all the way to the northern shore of the Forth. The situation at Upper Hirst level (Figure 4.9) is less quiescent. This trend of increasing fault density in an upward direction is consistent with surface geology mapping from the Geological Survey which shows an even denser pattern of faulting at surface. Surface faults show fault hades in the north of the licence dipping to the north and those in the south dipping to the south. This implies that the area contains a terraced horst feature with faults progressively migrating out of the licence to the north and to the south with increasing depth.

![Seismic map showing dip magnitude in the Wester Main Coal.](image)

**Figure 4.10** Seismic map showing dip magnitude in the Wester Main Coal.

The Midland Valley sill, known from drilling, does not image well in the legacy seismic. Line TOC86M112 tentatively images a flat zone at the appropriate depth predicted by its penetration in the Inch of Ferryton 1 well. It is hoped that reprocessing might strengthen the confidence in this pick and its extrapolation away from well control.

Figure 4.11 shows a depth converted structure map of the Upper Hirst Coal horizon interpreted along seismic lines and integrating data calibration points from boreholes and mine workings. Figure 4.12 shows the same depth mapping for the deeper Wester Main Coal horizon. These data were then gridded in DUG Insight using the ‘nearest neighbour’ technique to produce a contoured structure map. Depth structure maps for the Upper Hirst Coal and Wester Main Coal are shown in Figures 4.13 and 4.14 respectively.
Figure 4.11 Non-interpolated structure map for Upper Hirst Coal showing location of original data points.

Figure 4.12. Non-interpolated structure map for Wester Main Coal showing location of original data points.
Figure 4.13. Fully interpolated structure map for Upper Hirst Coal showing location of original data points.

Figure 4.14. Fully interpolated structure map for Wester Main Coal showing location of original data points.
4.5.3 Identification of Potential UCG Panels

The structural interpretation, based on a combination of low density 2D seismic, mine abandonment plans and a relatively small number of borehole data points around the licence, has resulted in the possible identification of relatively undisturbed coal in the Upper Hirst and the Wester Main coal seams.

Figure 4.15 shows the location of these areas in the Upper Hirst and Wester Main coals.

Figure 4.15. Maps showing location of possible UCG virgin coal panels in Upper Hirst Coal (top) and Wester Main Coal (bottom) within CNR’s licence.
It is important to point out that the identification of these panels is largely based on legacy 2D seismic of insufficient density and resolution to image faulting that can be observed in the mine abandonment plans. It should therefore not be assumed that the panels identified in Figure 4.15 are completely free of faulting or folding of a complexity that might have a negative impact on successful execution of a horizontal UCG well.

For example, the existence of faults within this apparently quiescent area has been indicated indirectly by the Geological Survey who, in a diagram used to illustrate the effect of intrusive igneous activity at Culross, clearly invoke a fault between Culross 2 and Culross 3 bores where no fault can be detected due to the absence of a seismic line at that location (Figure 4.16).

![Figure 4.16. Figure published by the Geological Survey showing a fault (red arrows) postulated between Culross 2 and Culross 3 bores and which is undetected by the low density / low resolution seismic coverage available for this study. Adapted from Francis et al (1970).](image)

Similarly, mine abandonment plans show the occurrence of numerous faults which, though minor in magnitude, have throws in excess of seam thickness but less than that detectable by 3D seismic (e.g. Figure 4.17). Such small faults are rarely laterally continuous for more than a few tens of meters and, because they do not compartmentalise the resource, potentially pose an enhanced drilling risk (and associated cost) rather than increased commercial risk.
Figure 4.17. Extract of mine abandonment plan S822_99 9999_2 OF 2 (Upper Hirst Coal) showing the position of minor (sub-seismic) faults encountered in two in-seam roadways beneath Grangemouth Docks. The roadways were constructed from south to north. The in-seam part of each roadway is shaded red and the difficulties experienced in staying in-seam across minor faults are evident, despite the ability to drill exploratory bores up or down from within the roadway.

Final confirmation of the existence of a high density of sub-2D seismic faulting comes from the interpretation of a small area of 3D seismic, shot by Scottish Coal (Deep Mine) Company Ltd, on the western flank of CNR’s UCG licence (IMC 2001). The interpretation of the Upper Hirst Coal horizon shows numerous laterally extensive faults with throws too small to be resolved on 2D seismic (throws <30 m). In fact, most of the small faults displayed on the interpretation have throws smaller than 20 m and, if encountered during drilling of a horizontal production lateral, could result in premature termination of the wellbore if the seam could not be found on the other side of the fault. Figure 4.18 shows the density of faulting observed in the 3D seismic area compared to the fault density observed from the 2D seismic interpretation at Upper Hirst level in this study.
Figure 4.18. Comparison of fault density mapped by 3D seismic and 2D seismic on the western flank of the Kincardine UCG licence. 3D faults transferred from IMC (2001).
5 Resource Estimation

5.1 Introduction
Belltree Reservoir Consultants were commissioned to undertake a resource assessment of Cluff Natural Resources Kincardine UCG Licence. The resource estimation has two parts: 1) an evaluation of the total coal resource remaining in the subsurface that could potentially be exploited for UCG that is unconstrained by geological, engineering and environmental issues which may affect its potential for commercial development; and 2) a resource estimate for specific areas and geological intervals on the Kincardine licence which are deemed to represent viable UCG targets. Both parts of the estimation draw heavily on geotechnical (geology and geophysics) work carried out as part of the overall evaluation.

At CNR’s request, both resource assessments have been conducted by Belltree in accordance with the ‘Australian Code of Exploration Results, Mineral Resources and Ore Reserves’ (referred to here as JORC [2012]). The methodology and definitions used for calculated resources (as required by JORC [2012]) follows that set out in ‘Australian Guidelines for the Estimating and Reporting of Inventory Coal, Coal Resources and Coal Reserves’ (referred to here as JORC [2003]). All input data and assumptions are provided with this report for auditing purposes.

5.2 Definitions and Criteria
JORC (2003) prescribes categories of coal that require to be used for coal assessments. Three main categories are based largely on mitigating risk related to commercial, environmental and producability factors (known as ‘modifying factors’). Sub-categories are then defined within the main categories reflecting different levels of geological knowledge and data confidence. Figure 5.1 summarises the JORC framework for classifying coal quality and quantity estimates.

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**Figure 5.1.** JORC framework for classifying coal resource and reserve estimates.
5.2.1 Definition of Resource Categories

JORC (2003) defines the three main categories as follows:

- **Inventory Coal** – a complete estimate of coal in place which is not significantly influenced by any of the modifying factors relating to commercialisation of the coal or its producability. Inventory Coal is not recognised by the JORC Code (JORC 2012). It is normally used for internal purposes as an indicator of all coal, some, or all of which, may not have potential for economic development. The JORC (2003) Guidelines state that it is permissible to exclude some minor coal occurrences from this category on grounds of, for example, depth and thinness. Based on data confidence this category is further divided into Inferred, Indicated and Measured sub-categories (see below for definitions).

- **Coal Resource** – a portion of the Inventory Coal that occurs in such a form and quantity that there are reasonable prospects for eventual economic exploitation. Importantly, the location, quantity, quality, geological characteristics (e.g. structure), and continuity are known, estimated or interpreted from specific geological evidence. Again, data confidence sub-categories are: Inferred; Indicated; and Measured.

- **Coal Reserve** – the economically mineable part of an Indicated or Measured Coal Resource. Assessments as to feasibility of resource exploitation require to have been carried out which include modifying factors such as: mining method; economics; marketing; legal; environmental; social and regulatory. There are two data confidence sub-divisions of Reserve, Probable and Proven. Each sub-division can further be classified as Marketable based on coal quality, yield and moisture.

Each of these main categories has sub-categories defined by data confidence. For Coal Inventory and Coal Resource these subcategories are defined as follows:

- **Inferred** – that part of the total Inventory or Resource for which quality and in-place quantity can only be inferred using points of observation which may be supported by interpretative data. An inferred estimate of the range of coal thickness should also be possible to a level of confidence below that required for full exploitation programme to be developed. The points of observation must be less than 4 km apart but should provide sufficient understanding of the geological conditions to infer continuity of seams between them.

- **Indicated** – that part of the total Inventory or Resource for which quality, average thickness and in-place quantity can be realistically estimated using points of observation and interpretative data. The points of observation must be less than 1 km apart (although this may be increased with sufficient technical justification).

- **Measured** – that part of the total Inventory or Resource for which sufficient data confidence allows a reliable estimate of average coal thickness, areal extent, depth range, quality and in-place quantity. The confidence level must be sufficient for the generation of detailed subsurface exploitation plans and the specification of a marketable product. The Measured Inventory or Resource is estimated using data obtained from points of observation which are less than 500 m apart (although this may be increased with sufficient technical justification).

For Coal Reserve (both Mineable and Marketable), the data confidence categories are defined as follows:
• **Probable** – that part of an Indicated or Measured Resource that can be reasonably demonstrated (at the time of reporting) to be economically extracted based on: extraction method; economics; marketing; legal; environmental; social and regulatory factors.

• **Proved** – that part of an Indicated or Measured Resource that has demonstrably satisfied all the modifying factors: extraction method; economics; marketing; legal; environmental; social and regulatory factors.

### 5.3 Overall Resource Associated with the Kincardine Licence

#### 5.3.1 Seam Selection Criteria

The JORC Guidelines and Code allow for specific criteria to be applied to estimates of in-place coal, even in the Inventory Coal category. For example, coals too thin or too steeply dipping to extract commercially may be omitted from the Inventory or Resource.

For the purposes of this evaluation, it is necessary to explicitly state threshold criteria used to define the resource being estimated. Table 5.1 outlines the UCG-specific criteria employed; apart from the lower depth window they are not dissimilar to criteria previously used for underground mining.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Threshold Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum coal rank</td>
<td>Low volatile bituminous</td>
</tr>
<tr>
<td>Maximum coal rank</td>
<td>Anthracite</td>
</tr>
<tr>
<td>Maximum ash content</td>
<td>50 wt%</td>
</tr>
<tr>
<td>Maximum sulphur content</td>
<td>3 wt%</td>
</tr>
<tr>
<td>Minimum depth</td>
<td>300 m</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>2000 m</td>
</tr>
<tr>
<td>Maximum dip angle</td>
<td>20 degrees</td>
</tr>
<tr>
<td>Minimum net seam thickness</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Maximum number of partings per seam</td>
<td>3</td>
</tr>
<tr>
<td>Maximum individual parting thickness</td>
<td>&lt; 20% of seam height</td>
</tr>
</tbody>
</table>

*Table 5.1. Threshold criteria used for seam selection in overall resource for Kincardine licence.*

#### 5.3.2 Methodology

The method used to compile the resource estimates is as follows:

- All possible observation points were identified within and in close proximity to the licence. Observation points primarily comprise historical coal exploration boreholes (often cored from surface) whose records are available from the British Geological Survey and mine abandonment plans (both raster and vector digital forms) licensed from the Coal Authority (Figure 5.2).

- All available geological records for the observation points (coal exploration boreholes) were collated and stratigraphically interpreted. Individual seams were identified from detailed mining accounts and geological memoirs.

- Since the target coals exist in seam groups corresponding to the two vertically adjacent Namurian formations of Upper Limestone Formation and Limestone Coal Formation, net-to-gross ratios of conforming coal seams at the observation points were calculated for each formation (Appendix 1).
Net-to-gross ratios for each formation were contoured across the entire licence using data from the observation points and gridded over 121.21 x 96.77 m cells (Figure 5.3).

Depth structure maps were created for the coal-bearing formations using information from the seismic interpretation and the observation points. Gridded surfaces for each were created using 121.21 x 96.77 m cells (Figures 5.4).

Isochores for each formation were calculated from the depth structure mapping over the entire licence using grid arithmetic on the depth structure grids (Figure 5.5).

Isochores for net coal were calculated for each formation using grid arithmetic by multiplying net-to-gross by formation thickness at each cell location (Figure 5.6).

Data confidence polygons conforming with JORC (2003) categories of Inferred, Indicated and Measured were created for each formation using the location of observation points (see Section 5.2.1 for definitions of Inferred, Indicated and Measured) (Figure 5.7).

For each formation, net coal for each 100x100 m cell was summed across each of the data confidence polygons to provide a volume of coal prior to extraction by mining.

For each formation, areas of charted underground working and recorded seam thicknesses in abandonment plans were used to calculate volumes of mined (extracted) coal.

Mined coal volumes were subtracted from total coal volumes in the Measured category for each formation and the result added to Inferred and Indicated coal volumes to obtain total in-place coal volume.

High, Mid and Low Case resources were calculated for each coal group based on varying three key criteria: net-to-gross ratio, coal density and calorific value. The actual variables used in the case of each formation are set out in Tables 5.2 and 5.3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Case</th>
<th>Mid Case</th>
<th>High Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net-to-gross ratio (%)</td>
<td>Gridded Mid Case value * 0.8</td>
<td>Gridded from observation points (see Figure 5.2)</td>
<td>Gridded Mid Case value * 1.2</td>
</tr>
<tr>
<td>Coal density (kg/m$^3$) (Air dried)</td>
<td>1380</td>
<td>1410</td>
<td>1425</td>
</tr>
<tr>
<td>Calorific Value (MJ/Kg) (DAF)</td>
<td>32.611</td>
<td>32.890</td>
<td>33.180</td>
</tr>
</tbody>
</table>

*Table 5.2. Low, Mid and High Case variables used in the calculation of Upper Limestone Formation resource (values based on Upper Hirst Coal analyses). Based on 135 analyses from NCB dataset.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Case</th>
<th>Mid Case</th>
<th>High Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net-to-gross ratio (%)</td>
<td>Gridded Mid Case value * 0.8</td>
<td>Gridded from observation points (see Figure 5.2)</td>
<td>Gridded Mid Case value * 1.2</td>
</tr>
<tr>
<td>Coal density (kg/m$^3$) (Air dried)</td>
<td>1295</td>
<td>1330</td>
<td>1345</td>
</tr>
<tr>
<td>Calorific Value (MJ/Kg) (DAF)</td>
<td>34.518</td>
<td>34.809</td>
<td>35.239</td>
</tr>
</tbody>
</table>

*Table 5.3. Low, Mid and High Case variables used in the calculation of Limestone Coal Formation resource (values based on Wester Main Coal analyses). Based on 27 analyses from NCB dataset.*

No accessibility factor was applied to area calculations (i.e. no inaccessible coal buffers were placed around faults, abandoned mine workings or the licence boundary).

5.3.3 Resource Calculation

The calculation for overall coal-in-place (CIP) is as follows:
\[ CIP\ Mass\ (Tonnes) = \text{Area (m}^2\text{)} \times \text{Net\ Coal\ Thickness\ (m)} \times \text{Coal\ Density\ (Kg/m}^3\text{)} / 10^3 \]

and

\[ CIP\ Energy\ (PJ) = CIP\ Mass\ (tonnes) \times 10^3 \times \text{Calorific\ Value\ (MJ/Kg)} / 10^9 \]

The resulting resource estimates for the two formations are set out in Tables 5.4 and 5.5.

<table>
<thead>
<tr>
<th>JORC Resource Category</th>
<th>CIP Mass (Tonnes)</th>
<th>CIP Energy (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Case</td>
<td>Mid Case</td>
</tr>
<tr>
<td>Measured</td>
<td>18772040</td>
<td>24214803</td>
</tr>
<tr>
<td>Indicated</td>
<td>24006493</td>
<td>30660714</td>
</tr>
<tr>
<td>Inferred</td>
<td>21094506</td>
<td>26941352</td>
</tr>
<tr>
<td>Total</td>
<td>63873038</td>
<td>81816870</td>
</tr>
</tbody>
</table>

*Table 5.4 Resource estimates for Upper Limestone Fm coal within CNR’s Kincardine Licence.*

<table>
<thead>
<tr>
<th>JORC Resource Category</th>
<th>CIP Mass (Tonnes)</th>
<th>CIP Energy (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Case</td>
<td>Mid Case</td>
</tr>
<tr>
<td>Measured</td>
<td>74299672</td>
<td>101351902</td>
</tr>
<tr>
<td>Indicated</td>
<td>70650446</td>
<td>90699702</td>
</tr>
<tr>
<td>Inferred</td>
<td>47354168</td>
<td>60792513</td>
</tr>
<tr>
<td>Total</td>
<td>192304286</td>
<td>252844117</td>
</tr>
</tbody>
</table>

*Table 5.5 Resource estimates for Limestone Coal Fm coal within CNR’s Kincardine Licence.*
Figure 5.2. Location of observation points used for calculation of total resource in the Kincardine licence.
Figure 5.3. Contoured net-to-gross ratio for coal seams in the Upper Limestone Fm and Limestone Coal Formation (top and bottom maps respectively).
Figure 5.4. Depth structure maps for the top Upper Limestone Fm, top Limestone Coal Formation and near top Lower Limestone Formation (top, middle and bottom maps respectively).
Figure 5.5. Isochore maps for the Upper Limestone Fm and Limestone Coal Formation (top and bottom maps respectively).

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Figure 5.6. Isochore map for net coal in the Upper Limestone Fm and Limestone Coal Formation (top and bottom maps respectively).
Figure 5.7. Distribution of JORC data confidence zones for the Upper Limestone Fm and Limestone Coal Formation (top and bottom maps respectively).
5.4 Resource Associated with Identified UCG Coal Panels

5.4.1 Seam Selection Criteria and Definition of Target Areas

The investigations carried out in the previous sections have identified areas of virgin coal in two stratigraphically distinct seams (Upper Hirst Coal in the Upper Limestone Formation and Wester Main Coal in the Limestone Coal Formation) which meet depth, coal quality and coal thickness criteria and give some indication (using very low resolution, low density data) of being relatively undisturbed over sufficient areal extent to meet materiality criteria.

The specific screening criteria used to select the seams are listed in Table 5.6. The threshold values for each criterion are identical to those used for calculating total coal resource (Section 5.3.1, Table 5.1) except that minimum seam thickness is increased from 0.5 m to 1.8 m.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Threshold Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum coal rank</td>
<td>Low volatile bituminous</td>
</tr>
<tr>
<td>Maximum coal rank</td>
<td>Anthracite</td>
</tr>
<tr>
<td>Maximum ash content</td>
<td>50 wt%</td>
</tr>
<tr>
<td>Maximum sulphur content</td>
<td>3 wt%</td>
</tr>
<tr>
<td>Minimum depth</td>
<td>300 m</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>2000 m</td>
</tr>
<tr>
<td>Maximum dip angle</td>
<td>20 degrees</td>
</tr>
<tr>
<td>Minimum net seam thickness</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Maximum number of partings per seam</td>
<td>3</td>
</tr>
<tr>
<td>Maximum individual parting thickness</td>
<td>&lt; 20% of seam height</td>
</tr>
</tbody>
</table>

Table 5.6. Threshold criteria used for seam selection.

The prospective zones at both stratigraphic levels dip approximately due west or west-southwest and lie in the western part of the licence directly offshore of the Longannet Power Station and the area immediately to the east. Extended reach drilling of < 2.5 km horizontal section would enable the UCG zones to be reached from locations within or to the north of the power station north of the river or from locations immediately north of the Orchardhead F Bore.

Figure 5.8 shows the location of the potentially exploitable zones in the Upper Hirst Coal and Wester Main Coal. A minimum depth cut-off of 300 m TVDSS has been applied when defining both areas. Areas of high risk where either seam may not reach minimum threshold thickness values have been avoided.

5.4.2 Methodology

The methodology used for resource calculation for the two selected UCG coal panels was essentially the same as for total resource (see Section 5.3.2) except that: 1) a constant seam thickness was used for each coal across the licence area (rather than a gridded value based on net-to-gross); and 2) accessibility buffers were imposed around areas of abandoned mine workings, the licence boundary and zones of known faulting (Figures 5.9 and 5.10). Tables 5.7 and 5.8 summarise the variables used for each resource case in each coal.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Case</th>
<th>Mid Case</th>
<th>High Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seam thickness (m)</td>
<td>1.7</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Horizontal offset from faults, mine</td>
<td>250</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>
Table 5.7. Low, Mid and High Case variables used in the calculation of Upper Hirst UCG panel resource. Based on 135 analyses from NCB dataset.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Case</th>
<th>Mid Case</th>
<th>High Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seam thickness (m)</td>
<td>1.8</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Horizontal offset from faults, mine workings and licence boundary (m)</td>
<td>250</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Coal density (kg/m³) (Air dried)</td>
<td>1295</td>
<td>1330</td>
<td>1345</td>
</tr>
<tr>
<td>Calorific Value (MJ/Kg) (DAF)</td>
<td>34.518</td>
<td>34.809</td>
<td>35.239</td>
</tr>
</tbody>
</table>

Table 5.8. Low, Mid and High Case variables used in the calculation of Wester Main UCG panel resource. Based on 27 analyses from NCB dataset.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Case</th>
<th>Mid Case</th>
<th>High Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seam thickness (m)</td>
<td>1.8</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Horizontal offset from faults, mine workings and licence boundary (m)</td>
<td>250</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Coal density (kg/m³) (Air dried)</td>
<td>1295</td>
<td>1330</td>
<td>1345</td>
</tr>
<tr>
<td>Calorific Value (MJ/Kg) (DAF)</td>
<td>34.518</td>
<td>34.809</td>
<td>35.239</td>
</tr>
</tbody>
</table>

5.4.3 Resource Calculation

The calculation for UCG coal-in-place (CIP) is as follows:

\[
\text{CIP Mass (tonnes)} = \text{Coal Panel Area (m}^2\text{)} \times \text{Coal Seam Thickness (m)} \times \text{Coal Density (Kg/m}^3\text{)} / 10^3
\]

and

\[
\text{CIP Energy (PJ)} = \text{CIP Mass (tonnes)} \times 10^3 \times \text{Coal Calorific Value (MJ/Kg)} / 10^9
\]

The calculated in-place resources for each case and each coal are presented in Tables 5.9 and 5.10.

Table 5.9. Low, Mid and High Case in-place resources for the Upper Hirst Coal.

<table>
<thead>
<tr>
<th>CIP Mass (Tonnes)</th>
<th>CIP Energy (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Mid</td>
</tr>
<tr>
<td>10440512</td>
<td>17239868</td>
</tr>
<tr>
<td>340.5</td>
<td>567.0</td>
</tr>
</tbody>
</table>

Table 5.10. Low, Mid and High Case in-place resources for the Wester Main Coal.

<table>
<thead>
<tr>
<th>CIP Mass (Tonnes)</th>
<th>CIP Energy (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Mid</td>
</tr>
<tr>
<td>18243828</td>
<td>25984037</td>
</tr>
<tr>
<td>629.7</td>
<td>904.5</td>
</tr>
</tbody>
</table>
Figure 5.8. Map showing location of potential UCG panels in the Upper Hirst Coal and Wester Main Coal (top and bottom maps respectively) defined using 150m and 250 m lateral buffers from faults, mineworkings and licence boundary for high and mid/low case respectively.
Figure 5.9. Maps showing UCG target panels in the Upper Hirst Coal showing 150 m (high case estimate) and 250 m (low case estimate) horizontal buffers from mine workings, faults and licence boundary (top and bottom maps respectively).
Figure 5.10. Maps showing UCG target panels in the Wester Main Coal showing 150 m and 250 m horizontal buffers from mine workings, faults and licence boundary (top and bottom maps respectively).
6 Conclusions

Using a wide range of public domain data sources and criteria used for assessing UCG and coal mining projects, an overall mid case coal resource in three formations of Namurian age has been calculated for CNR’s Kincardine licence:

- For the Upper Limestone Formation, a total mid case resource of 82 MT (2691 PJ) is calculated, of which:
  o 24 MT (796 PJ) is categorised as Measured Resource;
  o 31 MT (1008 PJ) is categorised as Indicated Resource; and
  o 27 MT (886 PJ) is categorised as Inferred Resource.

- For the Limestone Coal Formation, a total mid case resource of 253 MT (8801 PJ) is calculated, of which:
  o 101 MT (3528 PJ) is categorised as Measured Resource;
  o 91 MT (3157 PJ) is categorised as Indicated Resource; and
  o 608 MT (2116 PJ) is categorised as Inferred Resource.

Using the same public domain data sources, this study concludes that two seams of coal may fulfil UCG screening criteria and materiality required to conduct a pilot UCG project in CNR’s Kincardine licence:

- The two seams are the Upper Hirst Coal (Namurian, Upper Limestone Fm) and the Wester Main Coal (Namurian, Limestone Coal Formation);
- A calculated resource for the Upper Hirst Coal has a mid-case value of 17 MT, equivalent to 567 PJ;
- A calculated resource for the Wester Main Coal has a mid-case value of 26 MT, equivalent to 904 PJ;
- Evidence from mine abandonment plans adjacent to the identified panels suggest a fault density within the panels which could compartmentalise the resource and which cannot be detected using the current data resolution.

After collating, reviewing and interpreting the public domain data that is available for the Kincardine licence and adjacent areas, it is concluded that current data density (from boreholes, mine abandonment plans and particularly seismic) may be insufficient to:

- Detect the presence of some barriers to UCG burn progression such as minor faulting which may also compartmentalise the resource;
- Accurately plan the trajectory of a horizontal well (especially the in-seam land-out coordinates at the end of the build section, and provide early warning of steering requirements imposed by structural undulations or discontinuities); and
- Characterise faulting in terms of its ability to transmit water and gases without further modelling.
7 Recommendations
The relatively low density of subsurface control impacts on development plans at both the demonstrator and full field development stages of a UCG project:

- At the demonstrator stage, current uncertainty around the precise land-out co-ordinates for entering the target panel could be addressed by drilling of a pilot exploratory hole immediately prior to drilling of the production lateral.
- At the full field development stage, a 3D seismic survey would be beneficial to enhance the understanding of subsurface structure. Such a survey would aid field development planning and ensure maximum coal conversion; panels can be optimally located in the subsurface to avoid small, medium and large scale structural features and hole-in-coal for laterals can be optimised using modern geosteering technologies. This additional data collection will reduce overall drilling risk and ensure more wells are completed as planned.
- Finally, to raise the category of JORC resource type in areas which are currently ‘Inferred’ or ‘Indicated’, additional observation points (exploratory bores) might be placed at strategic locations on the licence to verify the presence and lateral continuity of coal seams. Such an exercise would also enhance the current understanding of subsurface structure and reduce drilling risk for full development.
8 References


IMC (2001). An Interpretation of Seismic Data from a 3D Seismic Survey in Zone 2 at Longannet Mine. IMC Geophysics Ltd.


