# Contents

Abstract ........................................................................................................................................... 9
Declaration ........................................................................................................................................ 10
Copyright Statement .................................................................................................................. 11
Acknowledgements ...................................................................................................................... 12
Chapter 1: Introduction ................................................................................................................ 13
  1.1: The Clare Shale Formation ................................................................................................. 13
  1.2: Shale Gas ........................................................................................................................... 14
    1.2.1 Characteristics of a Typical Shale Source Reservoir .................................................. 14
    1.2.2: Geological Characteristics of Shale Gas Source Reservoirs: ................................14
  1.3: The Project .......................................................................................................................... 17
    1.3.1: Background .................................................................................................................. 17
    1.3.2: Aims ............................................................................................................................. 18
    1.3.3: Methods ....................................................................................................................... 20
Chapter 2: The Geology of the Clare Basin ............................................................................ 25
  2.1: Basin Evolution and Palaeogeography ............................................................................. 25
    2.1.1: Palaeogeographic Setting and Tectonic Framework .................................................. 25
    2.1.2: The Caledonian Orogenic Cycle: ............................................................................. 26
    2.1.3: The Variscan Orogeny ............................................................................................... 27
  2.2: The Upper Carboniferous Shannon Basin and Stratigraphy ........................................ 28
    2.2.1: Architecture and Formation of the Shannon Basin .................................................... 29
    2.2.2: Marine bands as sea level indicators ......................................................................... 31
    2.2.3: The Mississippian (Tournaisian and Visean) Shannon Basin .................................... 32
  2.3: The Shannon Basin: Serpukhovian – Early Pennsylvanian (Namurian) ....................... 32
    2.3.1: Biostratigraphy .......................................................................................................... 32
    2.3.2: Lithostratigraphy ........................................................................................................ 33
Chapter 3: The Clare Shale Formation .................................................................................... 41
3.1: Characteristics of the Clare Shale Formation ...........................................41
3.2: Shale gas potential .........................................................................................51

Chapter 4: Field Work and Laboratory Analysis Results ..................................56
4.1: Introduction .......................................................................................................56
4.2: Inishcorker, County Clare ..............................................................................56
   4.2.1: Sedimentary Logs and Field Observations: ...........................................56
   4.2.2: TOC Analysis ..........................................................................................72
   4.2.3: Thin Section and Mudstone Microfacies Analysis .................................76
   4.2.4: Spectral Gamma Radiation Analysis ......................................................89
   4.2.5: XRD .......................................................................................................92
4.3: Doon West, Ballybunnion, County Kerry .....................................................93
   4.3.1: Sedimentary Log and Field Observations .............................................93
   4.3.2: TOC Analysis ..........................................................................................99
   4.3.3: Thin Section and Mudstone Microfacies Analysis .................................100
   4.3.4: Spectral Gamma Radiation Analysis ......................................................110
   4.3.5: XRD .......................................................................................................112
4.4: St. Brendan’s Well, County Clare .................................................................113
   4.4.1: Sedimentary Log and Field Observations .............................................113
   4.4.2: TOC Analysis ..........................................................................................115
   4.4.3: Thin Section and Mudstone Microfacies Analysis .................................116
   4.4.4: Spectral Gamma Radiation Analysis ......................................................120

Chapter 5: Discussion and Conclusion .................................................................121
5.1: Discussion .......................................................................................................121
   5.1.1: Shale Gas Potential of the Clare Shale Formation .................................121
   5.1.2: Sedimentological Processes and Palaeoenvironment ............................125
   5.1.3: Suitability as a Shale Gas Reservoir .......................................................129
5.2: Conclusions ....................................................................................................130
5.3: Recommendations ...........................................................................................131
Plate 20: IC 4.12 Thin Section ...........................................................................................................169
Plate 21: IC 4.13 Thin Section ...........................................................................................................170
Plate 22: IC 4.14 Thin Section ...........................................................................................................171
Appendix 9 ........................................................................................................................................172
Plate 1: NB 15 Mudstone Microfacies ............................................................................................172
Plate 2: NB 16 Mudstone Microfacies ............................................................................................173
Plate 3: NB 26 Mudstone Microfacies ............................................................................................174
Plate 4: NB 29 Mudstone Microfacies ............................................................................................175
Plate 5: NB 17 Mudstone Microfacies ............................................................................................176
Plate 6: NB 18 Mudstone Microfacies ............................................................................................177
Plate 7: NB 19 and 20 Mudstone Microfacies ................................................................................178
Plate 8: NB 21 Mudstone Microfacies ............................................................................................179
Plate 9: NB 22 and 23 Mudstone microfacies ................................................................................180
Plate 10: NB 24, 25, and 27 Mudstone Microfacies .......................................................................181
Plate 11: NB 28 Mudstone Microfacies ..........................................................................................182

List of Figures and Tables

Figure 1.1: Outcrop location map. .................................................................................................13
Table 1.2: Summary of shale gas reservoir parameters. ................................................................17
Figure 2.1: Early Ordovician Palaeogeography of Avalonia, Laurentia and Baltica ......................25
Figure 2.2: Present day Ireland, with Iapetus suture ......................................................................27
Figure 2.3: Carboniferous system. .................................................................................................29
Figure 2.4: Outline of the Clare Basin (offshore). ........................................................................31
Figure 2.5: Upper Mississippian and Lower Pennsylvanian biostratigraphy ................................33
Figure 2.6: Location, geology and stratigraphy of the Upper Carboniferous Shannon Basin, West Ireland. ........................................................................................................34
Figure 2.7: The Clare Shale outcrop at Ballybunnion ...................................................................36
Figure 2.8: The slump horizon in the Ross Sandstone Formation ..............................................38
Figure 2.9: Upper part of Gull Island Formation .................................................................39
Figure 2.10: Central Clare Group incised valley. .................................................................40
Figure 3.1: Marine band correlation .......................................................................................42
Figure 3.2: Upper Carboniferous time scale ........................................................................42
Table 3.1: Thickness of the Clare Shale Formation .................................................................43
Figure 3.3: Thickness contour map of the Clare Shale Formation ...........................................44
Table 3.2: Depth (m) to the top of the Clare Shale Formation .................................................45
Table 3.3: Mean TOC (wt %) for the Clare Shale Formation ....................................................45
Figure 3.4: Depth to top Clare Shale Formation contour map ..................................................46
Figure 3.5: Average TOC (wt %) contour map ....................................................................47
Table 3.4: Mean vitrinite reflectance (Rm) values .................................................................48
Table 3.5: Mean vitrinite reflectance (Rm) values for the Clare Shale Formation ..................48
Figure 3.6: Mean vitrinite reflectance (Rm) thermal maturity contour map ...........................49
Figure 3.7: Vitrinite reflectance (Rm) thermal maturity contour map .......................................50
Table 3.6: Palaeo- heat flow ..................................................................................................51
Table 3.7: Vitrinite reflectance data from the section spanning the Clare Shale Formation in the Doonbeg No.1 well. ......................................................................................52
Figure 3.8: Basin burial history model for the Clare Shale Formation ......................................54
Figure 3.9: Plot of thermal maturity versus depth .................................................................55
Figure 4.1: Google Earth image of the location of Inishcorker log IV ......................................57
Figure 4.2: Inishcorker log I outcrop photo ..........................................................................57
Figure 4.3: Inishcorker log I .................................................................................................58
Figure 4.4: Inishcorker log I outcrop photos .........................................................................59
Figure 4.5: Outcrop photo Inishcorker log II .........................................................................60
Figure 4.6: Inishcorker log II ...............................................................................................61
Figure 4.7: Overall outcrop photo, Inishcorker log 11 ..........................................................62
Figure 4.8: General overview of outcrop location for Inishcorker log III ...............................63
Table 4.23: Microfacies type 1 TOC

Table 4.24: Microfacies type 2 TOC

Figure 5.1: Summary of shale gas characteristic maps

Figure 5.2: Shale gas potential risk map for the Clare Shale Formation

Figure 5.3: The origin of silt in deep basinal environments

Figure 5.4: Interpretation of lenticular laminated fabric, pellet-bearing mudstone

Figure 5.5: Mineral composition ternary diagram

Total word count: 30,873

Main body (excluding abstract, references, and appendices) = 23,174
Abstract

The Clare Shale Formation, west Ireland, forms the lowest stratigraphical unit of the Upper Carboniferous Shannon Basin. This basin has received much attention in the past, mostly due to its spectacular cliff exposures of sedimentary deposits that have been used as analogues for deep-water reservoirs in the petroleum exploration industry.

The Clare Shale Formation, with its high total organic carbon (TOC) content, significant thicknesses (from 180m at outcrop to over 280m in the subsurface), and reasonable depth of burial (up to 700m at least) instantly appears to be an attractive target for shale gas exploration. However, available thermal maturity data indicates that the formation may be over-mature for hydrocarbons, even gas. Its high thermal maturity values indicate that the formation was even higher originally in organic carbon. The excellent exposures provided in the basin makes this a perfect formation for studying the sedimentology of a source rock formation and how variability in the sedimentological processes affects the distribution of shale gas reservoir characteristics.

Little is known about the sedimentology of the mudstones of the Clare Shale Formation. Through this research some of the first details have emerged regarding the sedimentology of the formation. Field work and subsequent laboratory analytical techniques revealed a variety of mudstone microfacies exist and this in turn leads to the interpretation that deposition of the Clare Shale Formation involved more than just simple suspension fallout as has been previously suggested.

Analysis of the microfacies and their corresponding total organic carbon (TOC) contents and mineralogies revealed that at times the environmental conditions near the seafloor were more oxygenated than previously presumed and sedimentary processes such as density flows and turbidity currents provided silt from the shelf to the deeper parts of the basin.
Declaration

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
Copyright Statement

i. The author of this dissertation (including any appendices and/or schedules to this dissertation) owns any copyright in it (“the Copyright”) and s/he has given The University of Manchester the right to use such Copyright for any administrative, promotional, educational and/or teaching purposes.

ii. Copies of this dissertation, either in full or in extracts, may be made only in accordance with the regulations of the John Rylands University Library of Manchester. Details of these regulations may be obtained from the Librarian. This page must form part of any such copies made.

iii. The ownership of any patents, designs, trade marks and any and all other intellectual property rights except for the Copyright (the “Intellectual Property Rights”) and any reproductions of copyright works, for example graphs and tables (“Reproductions”), which may be described in this dissertation, may not be owned by the author and may be owned by third parties. Such Intellectual Property Rights and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property Rights and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and exploitation of this dissertation, the Copyright and any Intellectual Property Rights and/or Reproductions described in it may take place is available from the Head of School of Earth, Atmospheric, and Environmental Sciences.
Acknowledgements

This dissertation would not have been possible without the kind sponsorship and support received from BNK Petroleum Inc. In particular I wish to express my thanks to Jim, Steven, Will, Allan, and Marcus for their advice and support in the field.

I wish to express my sincere gratitude to my academic supervisors: B.P.J. Williams, J. Redfern, K.G. Taylor and J.P. Armstrong, without whose support I could not have completed this dissertation.

I am truly thankful to my parents and my sisters for their moral support but also for their assistance with field gear and transportation during my field work trips.

I would also like to thank Catherine Davies, School of Earth, Atmospheric and Environmental Sciences, for her assistance with sample preparations, and for her patience as I took over her lab. Also I wish to thank Catherine for offering her support and advice and for checking up on me from time to time without ever having been asked to do so. She really is a credit to the school. I also owe thanks to Mike Turner, School of Earth, Atmospheric and Environmental Sciences for having the patience to deal with my endless enquiries and for rescuing me from many administrative errors.

I also extend my gratitude to David McKendry at Manchester Metropolitan University for running TOC analysis for this dissertation.

Finally, I also owe my sincere thanks to my fellow students, in particular Sami Khattab, a fellow research masters student for his support and advice throughout the year, for his assistance and company in the field, and for finishing my meals for me.
Chapter 1: Introduction

1.1: The Clare Shale Formation

The Clare Shale Formation is located on the west coast of Ireland in counties Clare, Limerick and Kerry (Fig. 1.1). It forms the lowest stratigraphic unit of the Late Mississippian to Pennsylvanian Upper Carboniferous Shannon Basin. The Clare Shale Formation, with its fine-grained nature, dominantly black colour, and high total organic carbon (TOC) content has often been described as a typical black shale deposited through suspension fall-out in a sediment starved basin (Collinson et al, 1991). The Clare Shale Formation reaches considerable thicknesses at outcrop and in the subsurface. Additionally, it is also known to be buried to a reasonable depth. These factors combined with its almost consistently high TOC values have inevitably led to interest in the formation regarding its shale gas potential. The Clare Shale Formation is explained in more detail in the subsequent chapters of this text.

Figure 1.1: Map showing the location of outcrops studied for this research project.
1.2: Shale Gas

Shale gas is the term used to describe the unconventional gas resources stored in source rock formations such as mudstones that have characteristically low porosity and permeability (Boyer et al, 2006). The flow of gas from a shale gas source reservoir is encouraged by artificially fracturing the rock in a process known as hydraulic fracturing.

In the 1970’s research and experimentation into the production of gas from shales was initiated in the United States of America (U.S.). Since then the implementation of enhanced drilling and recovery methods such as horizontal drilling and hydraulic fracturing has enabled natural gas to be successfully recovered from low permeability geological formations such as mudstones (EIA Report, 2011).

Large-scale shale gas production began in the 1980’s and 1990’s in the Barnett Shale in North-Central Texas, and up to 2005 the yearly natural gas production of the Barnett Shale alone was almost 0.5 TCF (trillion cubic feet). In 2011 estimates of recoverable U.S. shale gas resources stood at 862 TCF (EIA report, 2011). Shale gas resources have been estimated to account for 34 per cent of the 2,543 TCF natural gas resource base of the U.S., and by 2035 it is predicted shale gas production will account for 46 per cent of U.S. natural gas production (EIA report, 2011).

The success story of shale gas production in the U.S. has naturally led to investigations into the feasibility of successful shale gas plays located outside the U.S.

1.2.1 Characteristics of a Typical Shale Source Reservoir

Shale gas source reservoirs are considered by the USGS to belong to the group of hydrocarbon resources known as continuous or unconventional resources, along with basin-centred gas, tight gas, and coalbed gas (Schenk, 2005). The USGS has found that unconventional accumulations may exhibit one or all of 16 common traits (Schenk, 2005). Six of these traits are considered to be particularly relevant to shale gas source reservoirs as summarised by Boyer et al (2006): (1) regional extent (2) absence of a clear seal or trap, (3) lack of well-defined oil/water or gas/water contacts, (4), estimated ultimate recovery factors (EUR) that are usually lower than for conventional accumulations, (5) presence of natural fractures, and (6) low matrix permeabilities.

1.2.2: Geological Characteristics of Shale gas Source Reservoirs:
Organic matter content:

Shale gas mudstone formations have high total organic carbon (TOC) contents, usually in excess of 1 % by weight (wt %). Some are usually dominated by even higher TOC contents, such as the Mississippian Barnett Shale of the Fort Worth Basin, Texas, with a TOC range of 2 – 6 wt %, and the Devonian Marcellus Shale of the Appalachian Basin, Eastern U.S., with an average range of 2 – 10 wt % (Bruner and Smosna, 2011).

Kerogen type:

There are four kerogen types which are summarised below according to Boyer et al, 2006:

Type I: sourced from algal matter in mostly lacustrine environments and is oil prone.

Type II: sourced mostly from planktonic material in marine environments and is oil prone to gas prone as temperatures increase.

Type III: sourced from terrestrial plant material deposited in non-marine and marine environments and is mostly dry gas prone.

Type IV: this type of kerogen has a high carbon content but no hydrogen, which leaves it with no hydrocarbon generating potential.

Shale gas formations are dominated by type II kerogen, which is mixed oil and gas prone, increasingly producing gas with increasing temperature.

Some shale gas mudstone formations actually contain a mixture of type II, and type III (mostly gas prone) kerogen. The Barnett Shale is mostly type II with some minor type III, while the Marcellus Shale, also dominantly type II, has a slightly higher proportion of type III (Bruner and Smosna, 2011).

Thermal maturity:

Thermal maturity can be measured in a variety of ways, with vitrinite reflectance and the conodont (a marine fossil element) colour alteration index being among the most common techniques. Both of these materials show an increase in their reflectance with increasing thermal maturity. Vitrinite reflectance is reported as a per-cent reflectance in oil ($Ro$), and a breakdown of the $Ro$ ranges corresponding to the different hydrocarbon windows is presented in the following table:


<table>
<thead>
<tr>
<th>Hydrocarbon Window</th>
<th>% Ro range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>Oil window</td>
<td>0.6 – 0.8</td>
</tr>
<tr>
<td>Oil and wet gas</td>
<td>0.8 – 1.1</td>
</tr>
<tr>
<td>Oil to gas cracking of residual oil</td>
<td>1.1 – 1.5</td>
</tr>
<tr>
<td>Dry gas</td>
<td>&gt;1.5</td>
</tr>
</tbody>
</table>

*Table 1.1: Vitrinite reflectance values and corresponding hydrocarbon windows.*

Typical vitrinite reflectance values for the dry gas zones of the Barnett and Marcellus Shales are $Ro$ 1.2% and 1.6% respectively (Bruner and Smosna, 2011). Passey et al (2010) explain that most shale-gas exploration is targeting over-mature, oil-prone source rocks that have passed through the oil window to produce gas.

**Thickness:**

The minimum ideal thickness required in order to drill a horizontal well and produce from a shale gas reservoir is approximately 30 m (pers. comm. J. Hill, and J. Armstrong, 2012).

**Depth of Burial:**

The depth of burial required varies for each shale gas play due to variation in factors such as over-burden, pressure, and geothermal gradient. Generally, however, the minimum desired depth of burial is > 500m, but ideal depths are > 700m up to >1km (pers. comm. J. Armstrong, 2012). Depth of burial is related to pressure and temperature and this will ultimately affect the rate of adsorption of gas molecules onto organic matter, e.g. increasing pressure will increase the adsorbtion potential but only up to a maximum point whereby adsorbtion potential will then begin to decrease (Boyer et al, 2006). An increase in temperature will reduce the adsorbtion potential (pers. comm. J. Armstrong).

**Mineralogical composition:**

Shale gas reservoirs with a quartz or carbonate content above 50 wt% appear to be more brittle and will therefore respond better to artificial fracturing than reservoirs with a clay content greater than 50 wt% (Passey et al, 2010).
The following table (Boyer et al, 2006; Passey et al, 2010) summarizes some of the parameters necessary for shale gas production that have arisen from history of shale gas production in the U.S. shale gas plays.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>&gt; 4%</td>
</tr>
<tr>
<td>Water saturation</td>
<td>&lt; 45%</td>
</tr>
<tr>
<td>Oil saturation</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Permeability</td>
<td>&gt;100 nanodarcies</td>
</tr>
<tr>
<td>TOC</td>
<td>&gt; 2%</td>
</tr>
</tbody>
</table>

Table 1.2: Summary of the shale gas reservoir parameters deemed essential from experience in U.S. shale gas plays (Boyer et al, 2006; Passey et al, 2010).

1.3: The Project

1.3.1: Background

The organic-rich mudstones that act as shale gas reservoirs are often referred to as “black shales” (Schieber, 2003). Schieber (2003) describes how initial similarities drawn between black shales and muds deposited today in the Black Sea has resulted in geologists often coming to the conclusion that black shales are only formed in deep, anoxic basin settings by low energy fallout from pelagic suspension. However, recent work has shown that this is not always the case, with evidence of bioturbation and sedimentary structures often being present, that are interpreted to indicate periods of deposition when the waters were not anoxic and when current activity was present (Schieber, 2003; Trabucho-Alexandre et al, 2012).

Passey et al (2010) explain that although shale gas formations may be described as organic rich throughout, there is heterogeneity in the distribution of this organic-richness both vertically and laterally and on a micro and macro scale, and such heterogeneity is the result of variations in the environment of deposition and the stratal stacking. Unique lithofacies emerge as a result of depositional processes, and the stratal stacking of the lithofacies packages is controlled by changes in the basin’s accommodation space (Passey et al, 2010). Each shale succession will, in turn show both vertical and lateral variations in
lithofacies regarding, stratal stacking patterns, mineralogical composition, and amount of organic matter (Passey et al, 2010).

Such variations, for example, in depositional environment, depositional setting, and accommodation space will ultimately affect the distribution of shale gas reservoir characteristics such as thickness, organic matter content, and mineralogy. This may lead to the recognition of zones within a shale gas play that are more or less favourable targets for shale gas production.

1.3.2: Aims

The aim of this research is to assess the sedimentological variability of the Clare Shale Formation as a potential shale gas reservoir, and to evaluate its shale gas potential.

To achieve this aim the following objectives were met:

- Assess the published literature on the Clare Shale Formation to extract information regarding thickness, depth of burial, thermal maturity, and TOC and combine these with results from fieldwork conducted for this research project to create a basin history model, and to map the TOC, formation thickness and maturity.
- Evaluate the shale gas potential of the Clare Shale Formation.
- Conduct fieldwork at three outcrops (see Fig. 1.1 for outcrop locations) in order to identify the variability at a macro and micro scale for lithofacies, microfacies, TOC, and sedimentary process that affect the formations shale gas reservoir characteristics.

Variability of the following factors was investigated:

- Sedimentological variability on macro-scale through sedimentary logging of outcrops
- On a micro-scale the microfacies variation was assessed by integrating the optical and electron optical analysis of unusually-thin thin sections with TOC content.
- TOC content variations across an outcrop and across the basin.
- Thermal maturity
- Whole rock geochemistry (x-ray diffraction (XRD))
- Gamma radiation spectrometry
- Thickness and depth of the formation.
Understanding the variability inevitably aids our knowledge of the distribution of various shale source reservoir characteristics throughout the formation which can help in the evaluation of sweet spots and other factors which may affect development (Hammes and Frébourg, 2012).

Fine-grained successions such as the Clare Shale Formation often show less sedimentological detail on an outcrop and hand-specimen scale than coarse-grained successions making an assessment of sedimentology more difficult and there can be a wealth of information regarding microscopic features that warrant an investigation beyond what the eye can see (Macquaker et al, 2007).

Schieber and Zimmerle (1998) more than accurately predicted the recent growth and diversification in mudstone studies when they wrote that owing to “intellectual curiosity” there may be a “steady trickle of shale studies over the decades” (Schieber & Zimmerle, 1998). Up to the 1990’s the study of fine-grained rocks lagged behind that of coarser-grained sediments such as sandstones and carbonates (Potter et al, 1980; Schieber et al, 1998). The Sedimentology of Shale (Potter et al, 1980), the first text dedicated to the study of mudstone geology, identified four reasons why our understanding of mudstones had lagged behind that of other sedimentary rocks (Potter et al, 1980; Schieber and Zimmerle, 1998):

1. The difficulties of identifying “single particles” in mudstones, particularly the clay particles.
2. Difficulties unravelling the complexities associated with clay particles as a result of their susceptibility to burial and diagenetic changes.
3. The neglect of an accurate and detailed treatment of mudstones in “vertical environment profiles”.
4. Paucity of knowledge and understanding of palaeocurrent and palaeocirculation systems in operation during mud deposition.

The four reasons listed above were summarised and expanded by O’Brien and Slatt (1990) and Schieber and Zimmerle (1998) to take into account advances that had occurred in optical petrography and SEM studies to address the issue of identification of “single particles” and diagenetic effects on mudstones. Recent studies on mudstones has focussed on combining data from field observations and detailed field sampling with thin-section petrography, electron optical (SEM), geochemical (mineralogical XRD and TOC analysis), palaeontological, and whole-rock geochemical investigations of the samples (Potter et al, 1980; O’Brien and Slatt, 1990; Macquaker and Taylor, 1996; Macquaker et al, 2007).
Combining such datasets reveals both the macro- and micro-characteristics of mudstones and enables researchers to make clear observations regarding grain-size and origin, textural characteristics and lithofacies variability both vertically and laterally which aids in the construction of more adequate and accurate descriptions of the sedimentology of fine-grained successions (Potter et al, 1980; Schieber et al, 1998; Macquaker et al, 2007).

Following the methodologies outlined above (O’Brien and Slatt, 1990; Macquaker and Taylor, 1996; Schieber et al, 1998; Macquaker and Adams, 2003; Macquaker et al, 2007) the Clare Shale Formation was studied in the field during two short (4 day) field visits in November 2011 and March 2012. At three outcrop locations (Fig. 1.1) (St. Brendan’s Well in north County Clare; Inishcorker Island in the Fergus Estuary in south-east County Clare; and Doon West strand, near Ballybunnion in north-west County Kerry) detailed sedimentary and spectral gamma ray logs were conducted and samples were collected from the logged sections.

The results of the fieldwork and subsequent data analysis are presented separately for each outcrop in chapter 4. The interpretation of the results is presented in the discussion in chapter 5, followed by the conclusions drawn from the interpretations.

1.3.3: Methods

For this study both field and laboratory analytical investigative methods were employed in order to assess as much of the key characteristics as possible that can be used to determine the shale gas potential and the sedimentological variability.

Field methods:

1. Sedimentary logs were conducted at three locations (Fig. 1.1):
   - Inishcorker Island (52°39’54”N, 9°05’30”W) in the Fergus Estuary in south-east Co. Clare. The Fergus Estuary is a tributary to the Shannon Estuary (Fig. 1.1)
   - Doon West (52°31’19”N, 9°40’45”W), a coastal outcrop approximately 1 km north of Ballybunnion, Co. Kerry. This small isolated strand has been informally named here as Doon West as no local name for the strand could be found.
   - St. Brendan’s Well (53°01’47”N, 9°16’26”W) an inland stream outcrop in north-west Co. Clare.
Such logs were hand-drawn in the field and then digitized using CorelDRAW® version 13.

2. Detailed sampling was undertaken to complement the outcrops logged and to form the basis of the laboratory analytical investigations. Samples were collected at a spacing that varied from outcrop to outcrop. For the larger logs of Inishcorker log IV and the Doon West log (115 m and 74 m respectively) samples were collected at larger spacing (usually > 1 m) due to time limitations mostly. For the shorter logs of Inishcorker logs I, II, and II, and St. Brendan’s Well, samples were collected at a closer spacing (approximately 1m scale).

3. Spectral gamma ray logs were conducted using the RS-125 Super-SPEC hand-held gamma ray spectrometer. The RS-125 Super-SPEC was operated in assay mode which produced real-time data for the concentrations of Potassium (K) in per-cent (%), and Uranium (U) and Thorium (Th) in parts per million (ppm). This data was then downloaded as a text file using GeoView® software and then exported to Microsoft Excel, where the data was converted from per cent and parts per million values to American Petroleum Institute (API) values. XY scatter plots of the data were then created to analyse the trend in spectral gamma ray variation across the sections logged. The conversion from ppm and per cent concentrations to API units was performed as outlined by Rider and Kennedy (2011, p. 124) through multiplication of the concentration value of the K, U, and Th by 16.32, 8.09, and 3.93 respectively. For example a 5 ppm concentration of Th is multiplied by 16.32 to give 81.6 API units.

To accompany these field based techniques, samples were collected at recorded intervals from the logged sections in order to carry out laboratory analytical investigations.

**Laboratory analytical methods:**

Laboratory techniques included TOC analysis, thin section petrographic and scanning electron microscope – backscattered electron imaging (SEM-BSE) analysis, mineralogical composition analysis using X-ray diffraction (XRD), and thermal maturity analysis.

Samples were marked to indicate the direction of the “way-up” as they were collected during fieldwork. The hand samples were divided up into portions to be sent for thin section preparation and portions to be crushed for TOC, XRD, and thermal maturity.
analysis. Unusually thin (20 μm) polished and blue epoxy impregnated thin sections were manufactured by Wagner Petrograhic, Utah, USA.

The thin sections were examined optically under low power using a Nikon binocular microscope equipped with ProgRes 2.5 image digitizer to examine the nature of the centimetre to millimetre scale textures.

The sections were then examined at high power using the JEOL® 6400 scanning electron microscope in backscattered electron mode (SEM – BSE), (equipped with a SemAfore digitizer system for acquisition of high quality digital images), to examine the nature of the millimetre to micrometre scale textures and to gain a clearer image of the petrology. The SEM was operated at a working distance of 15 mm under 20 kV and 0.2 μA.

TOC and thermal maturity for the samples collected during the first field visit in November 2011 were outsourced to GHGeochem, Wirral, UK.

The second batch of samples collected in March 2012 were crushed and prepared by the author at the University of Manchester, with the assistance of Mrs Catherine Davies, in order to remove any inorganic carbon before being analysed for TOC. The TOC was then run on LECO machine/and software at Manchester Metropolitan University by Mr. David McKendry.

In order for TOC to be analysed the inorganic carbon was removed from the samples using the sample preparation method outlined below.

**TOC methodology**

1. Pre-cleaned rock samples are crushed to a fine powder by hand using a mortar and pestle
2. Approximately 0.2g of dried powdered sample is weighed a 50 ml glass beaker. The mass of the sample is recorded to four decimal places using a balance.
3. A solution of 6 M hydrochloric acid (HCl) was created by diluting 12 M HCl with water.
4. 10 ml of 6M HCL is added to the beaker and the contents are gently rotated to ensure that the sample is suspended in the fluid. The fluid in the beaker is observed at this point for any signs of reaction such as fizzing, which is noted if present.
5. Step 4 is repeated using two procedural blank samples without sediment.
6. Once the 10 ml HCl has been added to a beaker it is left for approximately 30 minutes.
7. A vacuum filter is prepared using a Buchner vacuum flask, which is fitted with a ceramic Buchner filter funnel, and a new Fisherbrand 47 mm glass microfiber filter paper for each sample.

8. After 30 minutes reaction time, approximately 40ml of deionised water is added to the beaker. The contents of the beaker are filtered through the Buchner vacuum flask apparatus described in step 7. The beaker is rinsed thoroughly using deionised water to ensure that no sediment particles remain. The sides of the filter funnel are also rinsed with deionised water to ensure no particles stick to the surface once the solution has drained through the filter.

9. The beaker is then rinsed twice more with 50ml of deionised water and the contents are poured through the filter device in order to ensure that any possible effects of chlorine on the LECO TOC machine are minimised.

10. Once the solution has been filtered the vacuum can be removed and the filter paper can be removed from the filter device. Any particles that remain in the filter device may be removed with a scalpel and wiped onto the filter paper.

11. The filter papers are air dried at room temperature for a minimum of 24 hours.

12. The filter paper is placed onto a LECO tin foil in order to be folded and rolled into the correct shape for insertion into the LECO machine. Any sediment that escapes the filter paper during folding will be trapped in the tin foil.

13. Once the filter paper has been folded and then rolled into a cylindrical shape the tin foil is then rolled around it and the edges are folded over tightly.

14. The samples are now ready to be run on LECO for TOC analysis.

The basin history was modelled using BasinMod 1-D Lite © (Platte River Associates Inc.) and the various parameters used are explained in detail in chapter 3. The thickness of the formation across the basin was mapped using Surfer® (Golden Software).

In order to establish a comprehensive description of the mudstone samples two classification systems are used. Field observations and lithological descriptions follow the standard scheme of Stow (2010), whilst optical microscopy observations for microfacies descriptions follow the Macquaker and Adams (2003) scheme of mudstone classification, with fabric descriptions based on the classifications used by O’Brien and Slatt (1990). The details of the classification systems employed during microfacies descriptions are outlined in appendix 1.
Much confusion exists regarding the terminology used in mudstone studies due to the interchangeable nature of some terms and the multiple meaning of others. Therefore, the terminology used in this text is defined as follows:

The terms “mud” and “clay” are often used to describe both grain size and mineralogy. To avoid confusion the term “mud” is used in this text as a prefix to describe rocks whose grain size is predominantly less than 63 μm, i.e. grains of the clay and silt sized factions (Stow, 2010). The term “clay” is used in field, lithological observations, and in descriptions of sedimentary logs to describe a rock whose grain size was predominantly of the clay sized faction with very little or no silt. In the microfacies analysis of the thin sections, the term “clay” is also used to describe the mineralogy and texture of mudrock microfacies. Where the term “clay” is used, it is mentioned whether it refers to the mineralogy of a component or to grain size.

The use of the term “shale” has been avoided as a descriptor, instead mudstones are described using suitable prefixes to clearly characterise their nature regarding fissility, degree of cementation, lamination and/or bedding, and bioturbation. This is done to avoid any misinterpretations arising where use of the term “shale” may be taken to indicate fissility (Aplin and Macquaker, 2011), and hence where the term fissility may be taken as an automatic indication of lamination (Macquaker and Adams, 2003).
Chapter 2: The Geology of the Clare Basin

2.1: Basin Evolution and Palaeogeography

2.1.1: Palaeogeographic Setting and Tectonic Framework

The south-eastern portion of Ireland, along with England and Wales, once formed part of the terrane of Avalonia (Cocks, 2005). In the lower Palaeozoic, the terrane of Avalonia formed part of the northern portion of Gondwana (Cocks, 2005) and was situated approximately 60° south of the equator (Cocks, 2005). The remaining portion of Ireland, along with Scotland, was part of the terrane of Laurentia, which was situated close to the equator and was separated from Avalonia by the Iapetus Ocean (Leeder 1976; Leeder 1982; Cocks, 2005; Naylor & Shannon, 2011). The continent of Baltica was situated east of Laurentia and north of Avalonia and was home to present day Scandinavia (Naylor & Shannon, 2011). Laurentia and Avalonia were separated by the Iapetus Ocean (Cocks, 2005). The two portions of Ireland were brought together as a result of the tectonic events of the Caledonian Orogenic Cycle (Cocks, 2005; Chew, 2009; Naylor & Shannon, 2011).

![Figure 2.1: Early Ordovician Palaeogeography of Avalonia, Laurentia and Baltica, with the approximate outlines of Ireland and mainland UK shown (modified from Naylor & Shannon, 2011).](image)

Around the time of the Cambrian-Ordovician boundary subduction was initiated in the Iapetus Ocean (Cocks, 2005). Also in the Ordovician (Fig. 2.1), Avalonia was rifted apart from Gondwana as a result of extensional tectonics (Cocks, 2005). Subduction beneath the Iapetus Ocean during the Ordovician resulted in the progressive narrowing of the ocean.
and the development of small island arc terranes (Cocks, 2005). Some of these arc islands would later dock with Avalonia during the various stages of the Caledonian Orogenic Cycle during the late Ordovician, Silurian and Early Devonian (Cocks, 2005; Naylor & Shannon, 2011).

2.1.2: The Caledonian Orogenic Cycle:

The events surrounding the closure of the Iapetus Ocean and the collision of Laurentia, Avalonia and Baltica involve multiple stages and pulses of tectonic processes and are therefore known collectively as the Caledonian Orogenic Cycle (Naylor & Shannon, 2011). The Caledonian history of Ireland is comprised of two collisional stages, the Lower to Middle Ordovician Grampian Orogeny (approximately 460 Ma) and the Lower Devonian Acadian Orogeny (405 Ma) (Naylor & Shannon, 2011).

The Grampian Orogeny involved the collision of subduction related island-arc systems of the Iapetus Ocean with the southern margin of Laurentia, which contained northwest Ireland and Scotland (Naylor & Shannon, 2011).

During the remainder of the Ordovician and Silurian, subduction of the oceanic crust of the Iapetus Ocean continued along both its northern margin with Laurentia and its southern margin with Avalonia, which would lead to the closure of the ocean and the beginning of the continental collisions between Laurentia, Avalonia and Baltica (Naylor & Shannon, 2011).

Baltica and Laurentia collided along present day Scandinavia and Greenland in the Scandian Orogeny during the late Silurian (Naylor & Shannon, 2011).

This northern amalgamation of the continents of Laurentia and Baltica was followed by collision of Laurentia and Avalonia during the Early Devonian Acadian Orogeny to form the megacontinent Laurussia (Naylor & Shannon, 2011). This brought the northern and southern parts of the British Isles together along a NE-SW trending boundary, which is known today as the Iapetus Suture zone (Fig.2.2) (Naylor & Shannon, 2011).
2.1.3: The Variscan Orogeny

During the Variscan Orogeny the continent of Gondwana collided with the Caledonian megacontinent Laurussia which involved multiple stages of deformation that occurred over a wide area from present day Russia, western Europe and the eastern United States (Graham, 2009). Ireland sits along the northern limit of deformation and the expression of deformation reduces from south to north (Graham, 2009). Fold intensity decreases northwards with tighter folds located in the south (Naylor & Shannon, 2011). The Upper Carboniferous Shannon Basin lies to the north of a vague “Variscan Front” (Naylor & Shannon, 2011) and therefore experiences gentler folding than areas to the south. The exact timing of the Variscan Orogeny has not been identified but it has been estimated that
peak deformation occurred during the latest Carboniferous to early Permian (Graham, 2009).

2.2: The Upper Carboniferous Shannon Basin and Stratigraphy

Many names have been proposed for this basin, which include, the Western Irish Namurian Basin (Collinson et al, 1991), the Shannon Trough (Strogen, 1988), and the Carboniferous Shannon Basin (Martinsen et al, 2000; Martinsen et al, 2003; Pyles, 2008, Pyles & Jennette, 2009). Since the style of deposition changed after the Visean from carbonate deposition to siliciclastic deposition, it is the siliciclastic basin only that is referred to here as the Upper Carboniferous Shannon Basin.

The subdivisions of the Carboniferous system used in this text are adopted from Heckel and Clayton (2006) and incorporate their regional stage and substage nomenclatures for Western Europe (Fig. 2.3).
2.2.1: Architecture and Formation of the Shannon Basin

Much speculation and debate has been centred on this topic, including the formation and behaviour of this Carboniferous basin. Collinson et al (1991) and Martinsen et al (2003) interpret the basin as an element of a system of Carboniferous basins that developed from late Devonian to Dinantian (Early and Middle Mississippian) times in response to crustal extension. In the Dinantian many of these basins, including the Upper Carboniferous Shannon Basin, underwent differential subsidence (Strogen, 1988). Areas subjected to higher subsidence rates experienced a deeper bathymetry and deposition of deep-water sediments (e.g. around the Shannon Estuary), whereas areas on more slowly subsiding crust experienced shallower submergence and deposition of shallow water carbonates (e.g. in north Clare) (Strogen, 1988; Collinson et al, 1991; Martinsen et al, 2003). This pattern of differential subsidence continued into the Namurian, with a central trough centred over the present day Shannon Estuary (Hodson & Lewarne, 1961). It has been speculated that crustal extension was the result of reactivation along the Caledonian Iapetus suture zone (Fig. 2.2) (Collinson et al, 1991; Martinsen & Collinson, 2002; Martinsen et al, 2003). Leeder (1976) states that the initiation of Carboniferous basins in the British Isles may be
the result of the development of a back-arc basin. The deep trough that had formed during the Dinantian around the Shannon estuary became the site of deep-water siliciclastic deposition at the start of the Namurian as differential subsidence continued and initiated the evolution of the Upper Carboniferous Shannon Basin (Hodson & Lewarne, 1961; Collinson et al, 1991; Martinsen & Collinson, 2002).

Most authors support the view that the basin is a structurally confined, elongate basin, with its axis aligned along an ENE to WSW trend that would seem to coincide with the axis of the present day Shannon Estuary and the trace of the Iapetus suture zone (Collinson et al, 1991; Martinsen & Collinson, 2002; Martinsen et al, 2003; Pyles, 2008).

Croker (1995) suggests that seismic surveys around Galway Bay show the Namurian strata continue offshore west of County Clare towards the margin of the Mesozoic Porcupine Basin (fig. 2.4). Near the margin of the offshore Upper Carboniferous Shannon Basin (Croker’s “Clare Basin”, 1995) and the Porcupine basin, two wells have encountered Namurian aged strata, well 26/26-1 and well 36/16-1 (Fig. 2.4), which encountered Serpukhovian and Yeadonian strata respectively (Sevastopulo, 2009).
2.2.2: Marine bands as sea level indicators

Eustatic changes in sea level played an important part in sedimentation during the Namurian (Ramsbottom, 1977). Ramsbottom (1977) states that the goniatite-bearing marine bands were deposited during the initiation of transgressive sea level conditions after regional regressions. Carboniferous rises and falls in eustatic sea level have been attributed to shifts of a Gondwanan ice sheet (Leeder, 1988; Hampson et al, 1997). Hampson et al (1997) illustrate how the characteristics of the Namurian marine bands of the British Isles (such as slow deposition rates, sudden deepening of the depocentre, and high uranium concentrations) indicates they are condensed sections deposited at the time of maximum rise in sea level and can be taken to represent the maximum flooding surface. Others believe that the marine bands were deposited after the maximum rise in sea level, during high stand conditions when the relatively isolated Upper Carboniferous basins of the British Isles were fully connected to open ocean conditions (Collinson et al 1991). Full marine salinities in such an interpretation would be restricted to the marine bands with the
intervening unfossiliferous mudstone representing reduced salinities in restricted basins (Collinson et al, 1991).

2.2.3: The Mississippian (Tournaisian and Visean) Shannon Basin

Since the focus of this text is the Clare Shale Formation, which forms the base of the Namurian siliciclastic basin fill, the dominantly carbonate Mississippian (Tournaisian - Visean) basin is only briefly summarised here.

The basin which existed in the Shannon area during the Mississippian was subjected to significant subsidence allowing the accumulation of thick Tournaisian and Serpukhovian successions, however little is known about the Visean succession of the region (Sevastopulo & Wyse Jackson, 2009).

Subsidence related to crustal extension combined with eustatic sea level rise resulted in a transgression of the sea from the south which continued throughout the Mississippian until the majority of Ireland was submerged (Sevastopulo & Wyse Jackson, 2009). Deposition of Waulsortian limestones occurred during the Tournaisian to early Visean (Sevastopulo & Wyse Jackson, 2009). The Waulsortian limestones of the Carboniferous Shannon Basin are the thickest found in Ireland, reaching thicknesses of between 800 m and 1200 m in the Shannon Estuary region, which is interpreted to represent the basin axis (Sevastopulo & Wyse Jackson, 2009).

Carbonate deposition dominates again during the Visean with the Waulsortian limestone facies continuing over much of the basin into the early Visean (Sevastopulo & Wyse Jackson, 2009). The Visean facies varies across the Shannon region but in general the succession consists of cherty limestones and bedded, fine-grained limestones and mudstones at the base, passing up into basinal limestone facies (Sevastopulo & Wyse Jackson, 2009).

2.3: The Shannon Basin: Serpukhovian – Early Pennsylvanian (Namurian)

2.3.1: Biostratigraphy

Before summarising the stratigraphical and lithological descriptions in existence for the Namurian fill of the Upper Carboniferous Shannon Basin, it is essential to acknowledge the detailed biostratigraphical work that has been done over the years (Fig. 2.5). The pioneering work of Hodson (1954a, 1954b), Hodson and Lewarne (1961), and Lewarne (1959), that has been referred to by most workers has enabled the application of a clear
control on the stratigraphy through the recognition of distinct faunal assemblages contained within marine bands found throughout the basin fill.

A more detailed description of the biostratigraphy of the Clare Shale Formation is given in chapter 3.

![Figure 2.5: Upper Mississippian and Lower Pennsylvanian biostratigraphy, with British regional substages of the Namurian and corresponding goniatite zones. (Modified from Braithwaite (1993), Heckel and Clayton (2006), Hodson and Lewarne (1961), Pyles (2008), and Rider (1974).)](image)

2.3.2: Lithostratigraphy

The lithostratigraphy of the basin-fill was established by Rider (1974) and is divided into two groups; the Shannon Group and the Central Clare Group (Rider, 1974) (Fig. 2.6). The Shannon Group consists of the Clare Shale Formation, the Ross Sandstone Formation and the Gull Island Formation (Rider, 1974). The uppermost basin-fill forms the Central Clare Group and consists of five fluvio-deltaic cyclothsms which are the, Tullig, Kilkee, Doonlicky, and cyclothsms IV and V respectively (Rider, 1974).
Figure 2.6: Figure 2.10: Location, geology and stratigraphy of the Upper Carboniferous Shannon Basin, West Ireland. Modified from Martinsen & Collinson (2002), Kendall & Haughton (2008) Braithwaite (1993), Heckel and Clayton (2006), Hodson and Lewarne (1961), Pyles (2008), and Rider (1974).
The stratigraphic units of the Shannon and Central Clare Group represent an overall upward-shallowing basin-fill system (Rider, 1974).

2.3.2.1: The Shannon Group:

Clare Shale Formation:

The Clare Shale Formation, more often referred to as the Clare Shales, was originally designated to the lowermost part of the Ross Sandstone Formation and described as goniatite-band bearing, black shales by Rider’s pioneering lithostratigraphical work (Rider, 1974).

The Clare Shales directly overlie the Mississippian limestones with varying degrees of unconformity in northern county Clare (Hodson, 1954a and b). However, the contact in the axial region around the Shannon Estuary is described as conformable (Hodson, 1954b; Wignall & Best, 2000).

Hodson (1954a) subdivided the formation into three main groups: (i) Upper or Sandy Shale Group, (ii) Middle or Goniatite Shale Group, and (iii) Lower or Phosphate Group. Hodson and Lewarne (1961) later removed the Sandy Shale Group to give the following subdivision of the Clare Shales: (i) Phosphorite Shales, (ii) Goniatite Shales, and (iii) Ribbed Beds.

The Clare Shales vary in thickness from 180 m south of the Shannon Estuary in Ballybunnion county Kerry to approximately 10 m in northern county Clare near Lisdoonvarna (Collinson et al, 1991; Braithwaite, 1993).

Collinson et al (1991) describes the Clare Shales as dark to predominantly black in colour, with an often fissile texture, being of a “rather monotonous” nature, with alternating fossiliferous zones (“marine bands”) and unfossiliferous zones. Goniatites are common in the marine bands and siderite concretions are found along certain beds (Collinson et al, 1991). The mudstones of the Namurian Clare Basin are interpreted by Collinson et al (1991) to be the result of classical mud suspension fall-out during times of sediment starvation and low energy. The marine bands have been interpreted by Holdsworth and Collinson (1988) to represent normal marine conditions achieved during sea level high stands when the small intracratonic basins of north-west Europe were connected to the open ocean. They interpret the unfossiliferous horizons between marine bands to represent deposition during sea level low stand then the small basins became cut off from the open ocean. An alternative explanation is provided by Hampson et al (1997) where the marine
bands are attributed to condensed horizons deposited during a period of maximum flooding rather than sea level high stand, and the unfossiliferous zones were deposited during normal marine conditions.

Braithwaite (1993) describes the Clare Shales as being “dark-grey to black” and often containing “calcareous nodules and beds”.

In northern county Clare, a thin unit of pebbly phosphate sits directly below the main mudstone succession and on top of the Mississippian limestones (Hodson, 1954a and b; Hodson & Lewarne, 1961; Rider, 1974). Hodson (1954a) suggests this represents a highly condensed unit that may represent most of the Arnsbergian and Pendleian.

The Clare Shale Formation will be described in detail throughout the remainder of this text.

Figure 2.7: The Clare Shale outcrop at Ballybunnion. The cliff height is approximately 40m.

Ross Sandstone Formation

The Ross Sandstone Formation (referred to as the Ross Sandstone) overlies and is the lateral equivalent to the Clare Shale Formation (Wignall & Best, 2000).

The Ross Sandstone’s type location is at Loop Head, southwest county Clare, with outcrops found here and south of the Shannon estuary at Ballybunnion, county Kerry.
The formation consists of bedded turbidite sandstones and intervening mudstones (Rider, 1974; Sleeman & Pracht, 1999). There is a high sand / mud ratio of between 70 – 80 % (Rider, 1974), dominated by fine grained sandstone with occasional medium sized sand grains, with the formation increasing in sand content upwards (Martinsen et al, 2000). Sandstones beds average up to 1 m in thickness with thicker beds greater than 5 m usually composed of thinner amalgamated beds (Martinsen et al, 2000). The basal contact with the Clare Shale Formation is gradational and represented by upwards coarsening from the Clare Shales to turbidite sandstones beds (Martinsen et al, 2000). The lower portion of the formation is only exposed at Ballybunnion, where a complete section is exposed (Sevastopulo, 2009) and is typified by non-channelized, “tabular” sandstones (Martinsen et al, 2000). Tabular sandstones are also seen in the middle and upper portions, however channel sandstones dominate and slump horizons (Fig. 2.8) also begin to make an appearance (Martinsen et al, 2000). Channelized sandstones can reach up to 18 m in thickness and have been found to have a lateral continuity of greater than 1500m (Martinsen et al, 2000). The channel fill of the upper portion is comprised of thickening upward packages and amalgamated turbidites (Lien et al, 2003). Slump units (Fig. 2.8) are best developed in the upper portion (Martinsen et al, 2000), the most spectacular of which is the Bridges of Ross slump unit. Megaflutes also occur in the upper portion (Elliot, 2000; Martinsen et al, 2000).

The dominant palaeocurrent direction gives a flow from the south-west towards the north-east (Collinson et al, 1991; Martinsen et al, 2000; Rider, 1974) which coincides with the interpreted NE-SW basin axis (Collinson et al, 1991). Variations in palaeocurrent flow variations to the north-west and south-east have been found in the lower and upper portions respectively (Collinson et al, 1991). Pyles (2008) used palaeocurrent data to argue for a palaeoflow towards the north during deposition of the Ross Sandstone.

The Ross Sandstone Formation is also punctuated by marine bands which allow for its stratigraphic correlation both north and south of the Shannon estuary (Braithwaite, 1993; Collinson et al, 1991; Hodson & Lewarne, 1961; Martinsen et al, 2000; Pyles, 2008; Rider, 1974). The Ross Sandstone occurs within the Homocerasbeyrichianum (H1b1) and Reticulocerasdubium(R1a5) goniatite zones (Braithwaite, 1993; Martinsen et al, 2000).

The environment of deposition has been interpreted by most workers to represent turbidite deposition on a submarine fan (Rider, 1974; Collinson et al, 1991; Lien et al, 2003). The lower, non-channelised part of the formation has been interpreted to represent the most distal area of turbidite deposition (Lien et al, 2003). Lien et al (2003) interpreted the upper
part of the formation to represent a proximal deep sea-floor setting where turbiditic deposition occurred in channels and their spillover systems. There has been debate regarding the palaeoflow directions associated with the Ross Sandstone, however most authors report the palaeoflow direction to be dominantly towards the north-east (Rider, 1974; Collinson et al, 1991; Wignall & Best, 2000; Lien et al, 2003).

![Image](image.jpg)

**Figure 2.8: The slump horizon in the Ross Sandstone Formation at Bridges of Ross on the south-west coast of County Clare, Ireland.**

**Gull Island Formation:**

The Gull Island Formation overlies the Ross Sandstone Formation. The Gull Island Formation is mud-dominated with siltstone and some fine sandstone and is characterised by numerous slump horizons (Fig. 2.9) with minor channels and lobes (Martinsen, 1989; Collinson et al, 1991; Wignal and Best, 2000; Martinsen et al, 2003; Pyles, 2008).

The Gull Island Formation was deposited on an unstable progradational slope (Rider, 1974; Collinson et al, 1991). As with the preceding formations of the Namurian basin fill, the Gull Island Formation is also thickest in the axial region near the Shannon Estuary and the south-west County Clare coast, reaching thicknesses of 550 m. Thinning occurs away from the axis to approximately 130 m thick on the northern margin, which is a distance of 60 km from the axis (Martinsen et al, 2003).

Martinsen et al (2000) and Martinsen et al (2003) have divided the formation based on facies associations into upper and lower parts. The lower part of the Gull Island Formation is mud-dominated and contains thin, undeformed, hemipelagic shales; mud-rich deformed
units and channelized and sheet turbidites of fine-grained sandstone (Martinsen et al, 2003). The turbidites were transported axially in the basin towards the east-north-east and the slumped, deformed mudstones were transported towards the south-east from an unstable slope located towards the north (Martinsen et al, 2003). Up to 75% of the lower Gull Island is affected by soft-sediment deformation (Martinsen et al, 2003). Martinsen et al (2000; 2003) have interpreted the lower part of the Gull Island Formation to represent basin floor turbidites and deformed mudstones deposited at the foot of the slope.

The upper part of the Gull Island Formation consists of a mudstone dominated succession that coarsens slightly upwards to siltstone with “isolated” and “rare” sandstone filled turbidite channels (Martinsen et al, 2003). It is gradational with the overlying deltaic Tullig Cyclothem of the Central Clare Group. The upper Gull Island is less deformed, with between 10 to 25% of the succession having experienced soft-sediment deformation (Martinsen et al, 2003). Martinsen et al (2003) have interpreted the upper part of the Gull Island Formation to represent an eastward prograding slope and associated deltaic system.

Figure 2.9: Upper part of Gull Island Formation with possible transition into lower Tullig Cyclothem towards upper portion of cliff. Note the two large growth faults, the thickening of beds towards the faults, and the features of soft-sediment deformation that dominate the lower portion of the cliff. The cliff height is approximately 40 m.

2.3.2.2: The Central Clare Group

The Central Clare Group gradationally overlies the Gull Island Formation of the Shannon Group, and consists of repeating successions or cyclothems of mudstone with marine
fossils, overlain by, siltstone, laminated sandstones and channel sandstones (Rider, 1974; Sevastopulo, 2009). In total there are five cyclothems, the Tullig Cyclothem being the lowermost, succeeded by the Kilkee, the Doonlucky, and cyclothems IV and V (Sevastopulo, 2009 and references therein). There are significant laterally extensive fluvial sandstones found in both the Tullig and Kilkee cyclothems which were initially interpreted to represent distributary channel and bar fills (Rider, 1974). However, Elliot and Pulham (1990) and Davies and Elliot (1996) have re-interpreted these as incised valley fills (Fig. 2.10) located above sequence boundaries.

Figure 2.10: Fluvial channel sandstones of an incised valley fill above a major sequence boundary erode here into the laminated siltstones and mudstones of the interdistributary bay fill of the cyclothem below. This outcrop is located at Trusklieve, on the Loop Head peninsula, south-west County Clare, Ireland.
Chapter 3: The Clare Shale Formation

3.1: Characteristics of the Clare Shale Formation

Age

The Clare Shale Formation contains many condensed sections that have been referred to as marine bands due to their richness of marine fauna (Pyles, 2008). In particular, each marine band is rich in goniatites, and each band has its own unique goniatite assemblage. These unique goniatite horizons found in the marine bands have enabled the application of a good biostratigraphical control. The older goniatite horizons are recognised at axial outcrops such as Inishcorker island and Ballybunnion, whilst younger goniatite horizons characterize the base of the formation towards the northern basin margin at St. Brendan’s Well (Braithwaite, 1993; Sevastopulo, 2009). This younging of the basal goniatite zones away from the axial region around the Shannon Estuary illustrates how the Clare Shale Formation onlaps the basin margins (Hodson & Lewarne, 1961; Martinsen & Collinson, 2002) (Fig. 3.1). For example, the oldest goniatites seen on Inishcorker belong the E1b ammonoid biozone which is Pendleian in age, and the youngest belong to the H2b zone, which is Alportian in age, whereas the oldest goniatites in the northern parts near St. Brendan’s Well are from the H1b zone (Hodson and Lewarne, 1961) (Fig. 3.2). The Clare Shales Formation is slightly older at Ballybunnion (Fig 3.2), being late Brigantian (P2) in age (Sevastopulo, 2009).

The Clare Shale Formation is believed to be conformable in the axial region around the Shannon Estuary with the Dinantian Carbonates beneath but missing marine bands and the occurrence of condensed sections in the north indicates that there is a slight unconformity in the north of the basin (Hodson & Lewarne, 1961; Martinsen & Collinson, 2002).
Figure 3.1: Sketch diagram illustrating basin margin onlap of the Clare Shale Formation and thinning away from the axial region both north and south, with a general biostratigraphic correlation between the basin axis and northern margin (for goniatite zones see figure 2.3 and 3.1). Not to scale.

Figure 3.2: Upper Carboniferous time scale and ammonoid biozones illustrating the younging of the Clare Shale towards the basin margin. Not to scale. (modified from Sevastopulo, 2009; ages from Dabydov et al, 2005 as referenced by Sevastopulo, 2009)
**Distribution and thickness**

The Clare Shale Formation is greater than 180 m at loop head (Pyles, 2008). At outcrop in Ballybunnion it is also over 180 m thick (Sevastopulo, 2009), and on Inishcorker island Hodson and Lewarne (1961) measured it at approximately 213 m thick. In the Doonbeg #1 well it was 280 m thick. The formation thins both north and south of the basin axis region and also develops non-sequences (Sevastopulo, 2009). In St. Brendan’s Well in north-west county Clare, approximately 12 m was measured during fieldwork for this project and this correlates with other measurements from the literature. Using these thickness measurements and additional thicknesses (table 3.1) from other locations as reported in Sevastopulo (2009, p. 277) and Goodhue and Clayton (1999) a thickness contour map was created (Fig. 3.3) using the kriging geostatistical interpolation method on Surfer 8®.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude decimal</th>
<th>Longitude decimal</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slieve Elva</td>
<td>53.08</td>
<td>-9.27</td>
<td>10</td>
</tr>
<tr>
<td>St. Brendan’s Well</td>
<td>53.03</td>
<td>-9.27</td>
<td>12</td>
</tr>
<tr>
<td>Magowna</td>
<td>52.83</td>
<td>-9.07</td>
<td>60</td>
</tr>
<tr>
<td>Doonbeg #1 well</td>
<td>52.73</td>
<td>-9.53</td>
<td>280</td>
</tr>
<tr>
<td>Inishcorker</td>
<td>52.67</td>
<td>-9.09</td>
<td>213</td>
</tr>
<tr>
<td>Foynes</td>
<td>52.62</td>
<td>-9.11</td>
<td>200</td>
</tr>
<tr>
<td>Ballybunnion</td>
<td>52.52</td>
<td>-9.68</td>
<td>180</td>
</tr>
<tr>
<td>Ballagh</td>
<td>52.37</td>
<td>-9.08</td>
<td>40</td>
</tr>
<tr>
<td>Templemary</td>
<td>52.23</td>
<td>-8.76</td>
<td>20</td>
</tr>
<tr>
<td>Caslteisland</td>
<td>52.23</td>
<td>-9.46</td>
<td>45</td>
</tr>
<tr>
<td>Slievecallan borehole</td>
<td>52.84</td>
<td>-9.27</td>
<td>40</td>
</tr>
</tbody>
</table>

*Table 3.1: Thickness of the Clare Shale Formation.*
Figure 3.3: Thickness contour map of the Clare Shale Formation, with decimal latitude and longitude and thickness in meters, superimposed over the outline of County Clare and north County Kerry.
Depth

The same locations used to map the thickness of the Clare Shale Formation (Fig. 3.3) were used to assess the depth to the top of the Clare Shale Formation (table 3.2 and Fig. 3.4). Values of 0m indicate surface outcrops. Subsurface data was only available for two locations, Doonbeg #1 well and the Slievecallan borehole.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude decimal</th>
<th>Longitude decimal</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slieve Elva</td>
<td>53.08</td>
<td>-9.27</td>
<td>0</td>
</tr>
<tr>
<td>St. Brendan’s Well</td>
<td>53.03</td>
<td>-9.27</td>
<td>0</td>
</tr>
<tr>
<td>Magowna</td>
<td>52.83</td>
<td>-9.07</td>
<td>0</td>
</tr>
<tr>
<td>Doonbeg #1 well</td>
<td>52.73</td>
<td>-9.53</td>
<td>700</td>
</tr>
<tr>
<td>Inishcorker</td>
<td>52.67</td>
<td>-9.09</td>
<td>0</td>
</tr>
<tr>
<td>Foynes</td>
<td>52.62</td>
<td>-9.11</td>
<td>0</td>
</tr>
<tr>
<td>Ballybunnion</td>
<td>52.52</td>
<td>-9.68</td>
<td>0</td>
</tr>
<tr>
<td>Ballagh</td>
<td>52.37</td>
<td>-9.08</td>
<td>0</td>
</tr>
<tr>
<td>Templemary</td>
<td>52.23</td>
<td>-8.76</td>
<td>0</td>
</tr>
<tr>
<td>Castleisland</td>
<td>52.23</td>
<td>-9.46</td>
<td>0</td>
</tr>
<tr>
<td>Slievecallan borehole</td>
<td>52.84</td>
<td>-9.27</td>
<td>410</td>
</tr>
</tbody>
</table>

Table 3.2: Depth (m) to the top of the Clare Shale Formation.

TOC:

Average TOC contents taken from field work at Ballybunnion, Inishcorker, and St. Brendan’s Well along with average values from the Doonbeg #1 well and the Slievecallan borehole (Goodhue & Clayton, 1999), were used to map the TOC variation (table 3.3). The average TOC contents for these locations are shown on the contour map in figure 3.5, which was also created using the kriging geostatistical method of interpolation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Decimal Latitude</th>
<th>Decimal Longitude</th>
<th>Mean TOC (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St Brendan's well</td>
<td>53.030</td>
<td>-9.274</td>
<td>3.33</td>
</tr>
<tr>
<td>Slievecallan borehole</td>
<td>52.841</td>
<td>-9.268</td>
<td>8.33</td>
</tr>
<tr>
<td>Inishcorker</td>
<td>52.665</td>
<td>-9.092</td>
<td>3.91</td>
</tr>
<tr>
<td>Ballybunnion</td>
<td>52.516</td>
<td>-9.678</td>
<td>4.47</td>
</tr>
<tr>
<td>Doonbeg #1 well</td>
<td>52.729</td>
<td>-9.527</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Table 3.3: Mean TOC (wt %) for the Clare Shale Formation
Figure 3.4: Depth to top Clare Shale Formation contour map.
Figure 3.5: Average TOC (wt %) contour map.
Thermal maturity

Mean vitrinite reflectance values (% Rm) were taken for the Slievecallan borehole and the outcrop at St. Brendan’s Well as reported in Goodhue and Clayton (1999). Rm values for the Doonbeg #1 well were obtained from the well report (Ambassador, 1963). Vitrinite reflectance values for Inishcorker and Ballybunnion were obtained during the project, however the readings come from samples with only one or two questionable vitrinite fragments that were not very well preserved. For this reason, two thermal maturity contour maps were created, the first using the measured values obtained for Inishcorker and Ballybunnion (table 3.4 and Fig. 3.6), and in the second these values are replaced by the mean vitrinite reflectance value of Rm 4.0 (table 3.5 and Fig. 3.7) quoted for the Upper Carboniferous Shannon Basin (Goodhue & Clayton, 1999).

<table>
<thead>
<tr>
<th>Location</th>
<th>Decimal Latitude</th>
<th>Decimal Longitude</th>
<th>Rm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St Brendan's well</td>
<td>53.030</td>
<td>-9.274</td>
<td>4.99</td>
</tr>
<tr>
<td>Slievecallan</td>
<td>52.841</td>
<td>-9.268</td>
<td>5.01</td>
</tr>
<tr>
<td>Inishcorker</td>
<td>52.665</td>
<td>-9.092</td>
<td>1.18</td>
</tr>
<tr>
<td>Ballybunnion</td>
<td>52.516</td>
<td>-9.678</td>
<td>1.93</td>
</tr>
<tr>
<td>Doonbeg</td>
<td>52.729</td>
<td>-9.527</td>
<td>4.54</td>
</tr>
</tbody>
</table>

Table 3.4: Mean vitrinite reflectance (Rm) values for the Clare Shale Formation, with measured values for Inishcorker and Ballybunnion.

<table>
<thead>
<tr>
<th>Location</th>
<th>Decimal Latitude</th>
<th>Decimal Longitude</th>
<th>Rm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St Brendan's well</td>
<td>53.030</td>
<td>-9.274</td>
<td>4.99</td>
</tr>
<tr>
<td>Slievecallan</td>
<td>52.841</td>
<td>-9.268</td>
<td>5.01</td>
</tr>
<tr>
<td>Inishcorker</td>
<td>52.665</td>
<td>-9.092</td>
<td>4.00</td>
</tr>
<tr>
<td>Ballybunnion</td>
<td>52.516</td>
<td>-9.678</td>
<td>4.00</td>
</tr>
<tr>
<td>Doonbeg</td>
<td>52.729</td>
<td>-9.527</td>
<td>4.54</td>
</tr>
</tbody>
</table>

Table 3.5: Mean vitrinite reflectance (Rm) values for the Clare Shale Formation, with measured values for Inishcorker and Ballybunnion replaced by average Clare Shale values from Goodhue and Clayton (1999).
Figure 3.6: Mean vitrinite reflectance (Rm) thermal maturity contour map for the Clare Shale Formation. Measured Rm values for Inishcorker and Ballybunnion are incorporated in this map.
Figure 3.7: Vitrinite reflectance (Rm) thermal maturity contour map, with average Rm 4.0 values (Goodhue & Clayton, 1999) used for Inishcorker and Ballybunnion.
3.2: Shale gas potential

Basin burial history modelling

In the present day location of the Upper Carboniferous Shannon Basin, the Namurian strata for the most part have no younger overlying sediments. Therefore an estimation had to be made regarding the extent of overlying sediments that had been deposited and eroded since the late Carboniferous. The Namurian basin stratigraphic units and thicknesses were taken from the Doonbeg No.1 well report (Ambassador Irish Oil Co., 1963), and the lithologies of the younger stratigraphical units were taken from Chevron 36/16-1 (Fitzgerald et al, 1994), a well located offshore, west of Ireland in the Porcupine Basin.

Estimates of palaeo-heat flow were based on values modelled by Allen et al (2002) who used apatite fission-track analysis to map the denudation pattern over Ireland since the Triassic, and on estimates from J. Armstrong (pers. comm., 2012). Table 3.6 below, shows the palaeo- heat flow values in mW/m² that were estimated and used in the basin burial history models run on BasinMod 1-D Lite®.

<table>
<thead>
<tr>
<th>Time (ma)</th>
<th>Heat flow (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>67</td>
</tr>
<tr>
<td>50</td>
<td>85</td>
</tr>
<tr>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>250</td>
<td>65</td>
</tr>
<tr>
<td>300</td>
<td>80</td>
</tr>
<tr>
<td>320</td>
<td>70</td>
</tr>
<tr>
<td>360</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 3.6: Palaeo-heat flow values used during modelling of the basin burial history (from Allen et al, 2002; and J. Armstrong (pers. comm.), 2012).

Measured vitrinite reflectance values (%Ro) from the Doonbeg No.1 well (Ambassador, 1963) over the Clare Shale section were entered into the basin burial history model simulations (table 3.7).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>% Ro</th>
<th>% Ro Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>807</td>
<td>4.58</td>
<td>0.18</td>
</tr>
<tr>
<td>862</td>
<td>4.55</td>
<td>0.21</td>
</tr>
<tr>
<td>917</td>
<td>4.77</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Table 3.7: Vitrinite reflectance data from the section spanning the Clare Shale Formation in the Doonbeg No.1 well.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>R₀ (%)</th>
<th>Maturity (°API)</th>
</tr>
</thead>
<tbody>
<tr>
<td>987</td>
<td>4.43</td>
<td>0.22</td>
</tr>
<tr>
<td>1040</td>
<td>4.72</td>
<td>0.16</td>
</tr>
<tr>
<td>1114</td>
<td>4.32</td>
<td>0.31</td>
</tr>
<tr>
<td>1165</td>
<td>4.42</td>
<td>0.21</td>
</tr>
</tbody>
</table>

In total, 5 basin burial history model simulations were run using the above palaeo-heat flow and thermal maturity parameters. Figure 3.8 shows the burial history model of the 5 which resulted in vitrinite reflectance values that most closely correlated with values from the Doonbeg #1 well. For each model the amount of sediments eroded, was altered and the vitrinite reflectance values predicted by the simulation were checked against the values in table 3.2 to see if they correlated (Fig. 3.9). The predicted maturity trend (Fig. 3.9, pink line) can be said to closely correlate with the measured thermal maturity values when it intercepts one or more of the measured thermal maturity values.

In order to attain vitrinite reflectance values close to those seen in table 3.2, the fifth model predicted that 1000m post Namurian, Carboniferous sediments, and 4750m post Carboniferous sediments were eroded. According to the model, simple burial and erosion of this 5750m would suffice to generate vitrinite reflectance values similar to those seen today in the Doonbeg No.1 well. These parameters, however, assume no added heat source such as igneous plume activity or high thermal heat flows associated with back-arc basins.

The fifth model (Fig. 3.8) suggests that the Clare Shale Formation entered the late mature window around the Jurassic/ Cretaceous boundary and have been over-mature for any remaining gas production since at least the early Paleogene (Fig. 3.8, black circle). The anticipated point of maximum adsorption of gas (Fig. 3.8, blue circle) in the Clare Shale Formation is predicted to have occurred before the initiation of Variscan uplift in the Late Carboniferous (pers. comm, J. Armstrong, 2012). As pressure is reduced during periods of uplift the rate of adsorption decreases (Fig. 3.8, black arrows). After uplift in the Variscan orogeny the Clare Shales may have regained some adsorption potential as they were buried again but this potential would have decreased with increasing temperatures (pers. comm. J. Armstrong, 2012).

Models one to four were run with an estimated total eroded sediment column of 3000m, 4000m, 5000m, and 5500m respectively and the predicted maturity trends produced did not correlate with vitrinite maturities seen in the Doonbeg #1 well.
However, it should be noted that the models run lack more accurate palaeo-heat flow values and are mostly based on the assumption that significant post-Carboniferous sedimentation occurred. There are many parameters which can be adjusted when running burial history simulations, and to cover all eventualities a significant amount of simulations would need to be run. For example, a significantly smaller column of eroded sediments could have been appropriate if the basin had been subjected to significantly high heat flows, like those associated with present day back arc basins (pers. comm. J. Armstrong, 2012).
Figure 3.8: Basin burial history model for the Clare Shale Formation
Figure 3.9: Plot of thermal maturity versus depth
**Chapter 4: Field Work and Laboratory Analysis Results**

**4.1: Introduction**

As outlined in chapter 1, the sedimentology of the Clare Shale Formation was assessed beginning with observations recorded in the field and subsequently through laboratory analytical investigations.

The results are presented separately for each location logged and sampled.

The sedimentary logs and field observations are first described. This is followed by a breakdown of the TOC values obtained and then by a summary of the thin section and mudstone microfacies descriptions for each sample from the logs. The detailed thin section and mudstone microfacies analysis is presented by individual plates in the appropriate appendix. Finally a description of the spectral gamma ray profiles that accompany the logs is given for the logs where a spectral gamma ray log was conducted.

**4.2: Inishcorker, County Clare**

In a preliminary field visit in November 2011 three short sedimentary logs were conducted on Inishcorker (Fig. 4.1), an island in the Fergus Estuary in south-east County Clare (Fig. 1.1, chapter 1). In March 2012 a more detailed and considerably larger sedimentary log was conducted over approximately 115 m (Inishcorker log IV), which incorporated the areas logged in November (Fig. 4.1). These logs (in particular the 115 m log) form the basis of the field observations for the Inishcorker section. A key for all sedimentary logs used in the text is provided in appendix 2.

**4.2.1: Sedimentary Logs and Field Observations:**

**4.2.1.1: Inishcorker log I – November 2011:**

In the first log, 3.65 m of mudstone was logged (Fig. 4.3), which consisted of a black, silty, mudstone with a platy to pencil-structure-like fissility punctuated with indurated, well cemented, concretion-rich beds, which increased in abundance towards the top of the section logged (Fig. 4.2). Small 1 to 5 cm fragments of plant fossil material were found towards the base of the section along a horizon that also contained small (~2 cm) goniatite fossils (Fig. 4.4). It was decided to assign all of Inishcorker log I as one facies, named facies one. This facies, where recognised in other Inishcorker logs will also be referred to as facies one.
Figure 4.1: Google Earth image of the location of Inishcorker log IV (yellow line). Log I, II, and III are all contained within the area covered by log IV. Kildysart village, on the mainland is located in the top left of the image and the causeway linking Kildysart to Inishcorker is in the middle-left of the image.

Due to the poor quality of the exposure an ultra-thin thin section was manufactured for only one sample (IC 1.1) and a corresponding TOC was obtained for the same sample and both were taken to be representative of the 3.65 m section logged.

Figure 4.2: Section logged for Inishcorker Log I in November 2011
Figure 4.3: Inishcorker log I. For a key to all sedimentary logs shown in this text please refer to appendix 1.1.
Figure 4.4: photo on the left shows a c. 1 cm goniatite cast on the surface of a bedding plane. Photo on the right shows a c. 2 cm fragment of possible plant material.

4.2.1.2: Inishcorker log II

A second preliminary log was conducted in November 2011 over approximately 2.6 m (see Fig. 4.6 for sketch log and Fig. 4.5 and 4.7 for the outcrop photos) with the aim of collecting closely spaced samples to investigate the small scale variability. Samples collected from this log have the prefix IC 2.

This approximately 2.6 m logged section (appendix 4.4 and fig 4.5) consisted in general of a silt-rich mudstone that had laminations throughout and a platy (O’Brien and Slatt, 1990, p.4) to pencil-structure-like fissility (facies one), and more indurated and less fissile mudstone that showed a flaggy to bedding-parallel parting (facies two) (O’Brien and Slatt, 1990, p.4).

The lower 15 cm (Fig. 4.7, photo B) consisted of a dark-grey silty mudstone, which was well cemented, with cm scale bedding. This unit showed a platy to pencil-structure-like fissility and was assigned to facies one. This unit also contained a thin and elongate (1 cm x10 cm) plant fragment, possibly *Calamites* sp. (Fig. 4.7, photo F). The sample taken from this bed is IC 2.1.

Above this unit there was approximately 35 cm of a black mudstone which showed a bedding plane –parallel / flaggy (O’Brien and Slatt, 1990, p.4) parting. Pyrite was abundant throughout this unit and goniatite casts on a 1 mm to 3 cm scale were common. Bedding was on a cm scale. This unit was assigned to facies two.

The third unit consisted of approximately 30 cm of soft/ non-indurated, heterolithic, yellow, red and black, clay-rich mudstone interbedded with cm scale indurated silty
mudstone beds (Fig. 4.7, photo C). This bed also corresponds to a unit logged near the top of Inishcorker log IV and has been assigned to facies three (see Fig. 4.12 - bed above 90 m).

The fourth unit, had an erosive base, and was similar in nature to the second unit. It consisted of approximately 20 cm of a black, silty mudstone, with bedding on a 1 to 2 cm scale with bedding-plane parallel/flaggy parting (Fig. 4.7, photo D). Sample IC 2.4 was taken from this unit.

The fifth unit consisted of approximately 164 cm of dark-grey silty mudstone, laminated on a mm scale which exhibited platy to pencil-structure-like fissility (Fig. 4.7, photo E). This unit contained very indurated and cemented beds that seemed to consist of amalgamated concretions. These beds ranged from 5 cm to < 20 cm and increased in frequency, being very closely spaced (every 5 to 10 cm) towards the top of the outcrop above the section logged (Fig. 4.5). At approximately 162 cm there were small, approximately 2 cm weathered goniatite casts. Samples taken from this unit include sample 2.5 and sample 2.6 c, the latter being from the uppermost concretion horizon logged.

Figure 4.5: section logged in sedimentary log Inishcorker II. The section logged commences where the sample bag is. Person for scale is approximately 1.7 m.
Figure 4.6: Inishcorker log II.
Figure 4.7: A) overall outcrop photo, logged section correlates to distance covered by scale bar. B) Lower, dark-grey, laminated, platy fissile mudstone (facies one). C) Unit 3, yellow, black, red interbedded soft mudstone and indurated cm scale silty mudstone beds (facies three). D) Unit 4, 20 cm thinly bedded (1 to 2 cm) silty mudstone with a bedding parallel / flaggy fissility or parting (facies two). E) Unit 5, dark-grey mudstone laminated on a mm scale with a platy to pencil-structure-like fissility, interbedded with more indurated 5 cm to < 20 cm concretion-rich beds. F) Upper bedding surface of unit one (photo B), with thin, elongate (1 x 10 cm) plant stem fragment enclosed by red rectangle. The plant fragment is most clearly seen in the bottom-left of the photo where the outcrop appears dry.
**4.2.1.3: Inishcorker log III**

A third preliminary sedimentary log was conducted on Inishcorker (Fig. 4.8), which covered approximately 6.45 m. Three samples were collected from this log (see Fig. 4.9) for TOC and microfacies analysis and each sample has the prefix IC 3.

Inishcorker log III begins at the unit which is represented by unit 3 (heterolithic clay-rich mudstone) in Inishcorker log II, with the aim of overlapping the two logs to cover more area in detail.

![Figure 4.8: General overview of outcrop location for Inishcorker log III. The lowermost unit is represented by the yellow-orange recessed bed seen in the right-middle portion of the photo.](image)

The lowermost unit (Fig. 4.10) consisted of approximately 30 cm interbedded, heterolithic, yellow and red clay-rich mudstone, interbedded with thin beds of a black silty mudstone (facies three).

Unit two consisted of approximately 15 cm of a black, silty mudstone with an erosive base contact (facies two). This unit had bedding which varied from a few millimetres to a centimetre in thickness. This differs from that described for the corresponding unit in Inishcorker log II, where the bedding observed was on a 1 to 2 cm scale. No smaller scale laminations were observed within the bedding at the outcrop. This unit showed a flaggy to bedding plane parallel parting. Sample IC 3.2 was collected from this unit.
Figure 4.9: Inishcorker log III.
The third unit occupies the remainder of the log, covering approximately 6 m. It consists of a silt-rich mudstone which displays a platy to pencil-structure-like fissility, interbedded with more indurated non-fissile laminated mudstone rich in concretions, in beds of varying thickness (facies one) (between 5 and < 20 cm). These beds likely represent horizons where a high density of concretions formed, which later amalgamated to form better-cemented and more resistant horizons. This unit corresponds to unit 5 in Inishcorker log II and their similar nature in the photos and descriptions of both logs is apparent. Two samples were collected from this unit at a distance of approximately 2 m between them, sample IC 3.3 and IC 3.4.

Figure 4.10: lowermost unit of Inishcorker log III, a heterolithic unit of interbedded clay-rich mudstone and silty mudstone (facies three). Pencil for scale is approximately 15 cm long, and erosive contact with unit above is seen just below the compass clinometer.

Comparison of Inishcorker logs I, II, and III:

Although these logs cover very small distances of the total section exposed on Inishcorker (estimated at 700 ft (or 216 m) by Hodson and Levarne, 1961) correlations could be drawn between the lithologies observed in the field, and the mudstone microfacies and TOC
values analysed in the lab. These preliminary logs also serve as precursors to the larger, 115 m log that was conducted on Inishcorker in March 2012.

In logs I, II and III, three broad facies are apparent:

1. A black silty mudstone, laminated, with a platy to pencil-structure-like fissility, with non-fissile more indurated concretion-rich beds which vary in thickness from ~ 5 cm to > 20 cm (only lithofacies observed in log I)
2. A dark-grey silty mudstone, thinly bedded on a few mm to ~ 5 cm scale, lacking fissility, but displaying a flaggy, bedding-plane parallel parting.
3. A yellow to red heterolithic clay-rich mudstone, and interbedded black silty mudstone.

The following table correlates the samples taken with the corresponding log and facies:

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sample</th>
<th>Log</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IC 1</td>
<td>I</td>
</tr>
<tr>
<td>1</td>
<td>IC 2.1</td>
<td>II</td>
</tr>
<tr>
<td>1</td>
<td>IC 2.5</td>
<td>II</td>
</tr>
<tr>
<td>1</td>
<td>IC 2.6 c (concretion horizon)</td>
<td>II</td>
</tr>
<tr>
<td>1</td>
<td>IC 3.3</td>
<td>III</td>
</tr>
<tr>
<td>1</td>
<td>IC 3.4 (concretion horizon)</td>
<td>III</td>
</tr>
<tr>
<td>2</td>
<td>IC 2.4</td>
<td>II</td>
</tr>
<tr>
<td>2</td>
<td>IC 3.2</td>
<td>III</td>
</tr>
</tbody>
</table>

**Table 4.1: Correlation between facies described in logs and the samples analysed. Samples in green italics come from the same stratigraphic horizon (log II unit 5, and log III unit 3), and samples in red also come from the same stratigraphic horizon (log II unit 4, and log III unit 2).**

These three facies, defined from the three preliminary logs are recognised again in Inishcorker log IV their use is employed in descriptions of that log also.

**4.2.1.4: Inishcorker Log IV – March 2012**

During a second field visit in March 2012, approximately 115 m was logged (Fig. 4.12) on Inishcorker with some overlap with logs II, and III (Figs. 4.11). Samples collected from Inishcorker log IV have the prefix IC 4.

A spectral Gamma Ray log was also conducted, covering approximately the first 104 m of the log, and ultra-thin thin sections were manufactured for 14 samples. These samples were also analysed for TOC, and 5 of them were analysed using x-ray diffraction (XRD).
Over the 115 m logged, three lithofacies were observed, which have been described from logs I, II, and III. Lithofacies one dominated, with approximately 11 m of lithofacies two and approximately 2 m of lithofacies three.

For detailed outcrop photos please refer to appendix 1.3 to 1.7.

The lowermost unit measured 2.27 m and consisted of black silty mudstone, in beds of 3 to 7 cm in thickness with a flaggy bedding-plane parallel parting (appendix 3, photo A) and B). Sample IC 4.1 was collected from this unit. Beds in this unit thickened upwards from approximately 3 cm thick to approximately 7 cm thick. Internally, the beds were laminated on a ≤ 1 mm scale.

Unit two (appendix 3, photos C and D) measured approximately 7.46 m and had a gradational basal contact with unit one. It consisted of a black silty mudstone, with laminations on a < 1 mm scale. Some laminations appeared to be rich in pyrite. This mudstone displayed a platy to pencil-structure-like fissility. Small oblate concretions were dispersed through this unit and some had abundant pyrite in their cores. This unit has been assigned to facies one. Above the lower 3 m the concretions increased in size (one being ~ 2.5 m in diameter), and appeared to amalgamate along certain horizons to form better-cemented, more indurated, and non-fissile beds. These beds range from a few cm to 10 cm.

Figure 4.11: Inishcorker logs II, III, and IV outcrop photo. The photo was taken at approximately 90 m in log IV, where logs II, III, and IV overlap.
in thickness and often show internal laminations. Two samples were collected from this unit, sample IC 4.2 was taken from a fissile part and sample IC 4.3 was taken from a better-cemented concretion-rich horizon.
Figure 4.12: Inishcorker log IV, with sample locations indicated by stars.
Unit three (appendix 4) measured approximately 5.54 m and was similar in nature to unit one. It had a sharp, erosive basal contact with unit two. This appeared to be a silty mudstone, which was thinly bedded with beds thickening upwards from > 1 mm at the base to > 5 cm. Internally the beds were laminated on a ≤ 1 mm scale, and with abundant pyrite forming a mottled texture that was tentatively interpreted in the field as burrows. Concretions tended to be large, with one almost 1 m in diameter (appendix 4.11, photos A and B). Possible load structures and load casts were observed between two beds near the top of the unit (appendix 1.4, photo D). This unit was assigned to facies one. Sample IC 4.4 was taken approximately 20 cm from the base of the unit and sample IC 4.5 was taken approximately 20 cm from the top.

Unit four was similar in nature to unit two, and consisted of dark-grey to black silty mudstone with a platy, pencil-structure-like fissility, with beds of concretion-rich, better-cemented, non-fissile mudstone ranging from 8 to 10 cm in thickness, with one bed that was approximately 1 m thick (appendix 5, photo C). Unit four measured 29.49 m and was assigned to facies 1. This unit showed laminations throughout, some being pyrite-rich, with some pyrite-rich areas having a mottled texture, possibly indicating pyritization of burrows (appendix 5, photo B). Three samples were analysed from unit four, sample IC 4.6 from a fissile portion at approximately 17.5 m, sample IC 4.7 (appendix 5, photo D) from a non-fissile, better cemented bed at approximately 19.3 m, and sample IC 4.8 from a fissile portion at approximately 31.3 m.

Unit five was assigned to facies 2 because it is similar in nature to units one and three. It consisted of approximately 2.5 m of black, thinly bedded (on a sub- cm to 5 cm scale) (appendix 6). The beds are internally laminated, with abundant pyrite and small pyrite nodules (≤ 1 mm scale), that may be pyritized burrows. Some bedding surfaces showed indications of slickensides which indicates bedding plane slide (appendix 4.13, photos B and C). Load casts and corresponding load structures were also seen on the surface and base of the interface between two beds (appendix 6, B, D). One bed had extensive wavy deformation (appendix 6, E), which may have been wave ripple structures as there was no indication of deformation to the beds above or below it. IC 4.9 was the only sample analysed from this unit.

Unit six consisted of 40.82 m of dark-grey to black silty mudstone (appendix 7, photos A, B) that was similar to units two and four and was consequently assigned to facies one. There was upwards fining to approximately 50 cm of very weathered black and red-brown clay-rich mudstone at the top of the unit (appendix 7, photo C). It had a gradational
contact with the unit below. As with other units of this facies, this unit showed platy to pencil-structure-like fissility with abundant interbedded non-fissile, better-cemented beds. However, these non-fissile silty mudstone beds were thicker in this unit being mostly 1 dm in thickness. Note, in the sedimentary log not all of the cemented beds are represented. Three samples were analysed from this unit, IC 4.10 and IC 4.12 (from fissile portions), IC 4.11 (from a non-fissile portion). Upwards fining of the upper 50 cm of this unit can be seen in appendix 7, photo C.

Unit seven consisted of 0.3 m of facies two-type, black silty mudstone, thinly bedded with abundant laminations and pyrite internally. This unit had a sharp, undulating, erosive base. The thickness of this unit varied laterally as can be seen in appendix 7, photo C. In this photo it can be seen above unit six and it is over 50 cm thick. Sample IC 4.13 was collected from this unit.

Unit seven has a gradational contact with unit 8, which is a 2 m thick black silty mudstone which displays the characteristics of facies one.

There is a sharp, but non-erosive contact with the next unit, unit nine, which is a yellow to red clay-rich mudstone interbedded with black silty mudstone (appendix 4.5, C). This heterolithic unit is stratigraphically the same as unit three in Inishcorker log II, and unit one in Inishcorker log III. Unit eight was approximately 30 cm thick. This unit has been assigned to facies three.

The remainder of the log, approximately 24.5 m, unit ten, was a dark-grey to black silty mudstone, which displayed platy to pencil-structure-like fissility, and contained numerous non-fissile, concretion-rich, better-cemented beds. Unit nine has been assigned to facies one and sample IC 4.14 was collected from it.

**Inishcorker log IV – facies summary**

The following table is a summary of the units observed in the field, the samples collected from them and the facies assigned to each unit:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Facies</th>
<th>Sample ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>IC 4.1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>IC 4.2, 4.3</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>IC 4.4, 4.5</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>IC 4.6, 4.7, 4.8</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>IC 4.9</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>IC 4.10, 4.11, 4.12</td>
</tr>
</tbody>
</table>
Table 4.2: Summary of facies and corresponding sample and log unit from Inishcorker log IV

4.2.2: TOC Analysis

TOC values were analysed for samples from the four logs. The results are shown in the tables below.

4.2.2.1: Inishcorker log I

The following table shows the weight percent TOC (Wt % TOC) value obtained for the Inishcorker log I sample:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Unit</th>
<th>Facies</th>
<th>Wt % TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 1.1</td>
<td>1</td>
<td>1</td>
<td>2.41</td>
</tr>
</tbody>
</table>

Table 4.3: TOC result for Inishcorker log I.

4.2.2.2: Inishcorker log II

Four samples were collected and analysed for TOC (Fig. 4.13), one from unit 1 (sample IC 2.1), unit 4 (sample IC 2.4), and two from unit 5 (samples IC 2.5 and IC 2.6 c). The following table shows the TOC results beginning with the lowermost unit:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Corresponding log Unit</th>
<th>Facies</th>
<th>Wt % TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 2.1</td>
<td>Unit 1</td>
<td>1</td>
<td>6.01</td>
</tr>
<tr>
<td>IC 2.4</td>
<td>Unit 4</td>
<td>2</td>
<td>6.78</td>
</tr>
<tr>
<td>IC 2.5</td>
<td>Unit 5 (fissile mudstone)</td>
<td>1</td>
<td>3.95</td>
</tr>
<tr>
<td>IC 2.6 c</td>
<td>Unit 5 (concretion horizon)</td>
<td>1</td>
<td>3.25</td>
</tr>
</tbody>
</table>

Table 4.4: TOC values for samples taken from Inishcorker Log II
4.2.2.3: Inishcorker log III

Three samples were taken and analysed for TOC; IC 3.2, IC 3.3, and IC 3.4 (Fig. 4.14 and table 4.5).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Unit</th>
<th>Facies</th>
<th>Wt % TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 3.2</td>
<td>Unit 2</td>
<td>2</td>
<td>8.21</td>
</tr>
<tr>
<td>IC 3.3</td>
<td>Unit 3</td>
<td>1</td>
<td>3.61</td>
</tr>
<tr>
<td>IC 3.4</td>
<td>Unit 3</td>
<td>1</td>
<td>2.68</td>
</tr>
</tbody>
</table>

*Table 4.5: TOC values for Inishcorker log III*
4.2.2.4: Inishcorker log IV

The results of TOC analysis carried out on the fourteen samples collected and analysed from Inishcorker log IV (appendix 1.8) are presented in the table below:
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Wt % TOC</th>
<th>Unit</th>
<th>Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 4.1</td>
<td>2.34</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>IC 4.2</td>
<td>4.86</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.3</td>
<td>0.80</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.4</td>
<td>3.1643</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>IC 4.5</td>
<td>3.37</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>IC 4.6</td>
<td>3.81</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.7</td>
<td>4.32</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.8</td>
<td>5.90</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.9</td>
<td>0.24</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>IC 4.10</td>
<td>4.56</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.11</td>
<td>8.16</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.12</td>
<td>2.57</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>IC 4.13</td>
<td>2.46</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>IC 4.14</td>
<td>2.48</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 4.6: Inishcorker log IV TOC results*
4.2.3: Thin Section and Mudstone Microfacies Analysis

The mudstone microfacies and fabric descriptions made were based on the classification systems of O’Brien and Slatt (1990) and Macquaker and Adams (2003) and these are summarised in appendix 1.

Detailed descriptions of each thin section and its microfacies can be found on plates 1 to 22 in appendix 9.

4.2.3.1: Inishcorker logs I, II, and III

The following table shows the samples examined optically and their microfacies description along with their corresponding log and outcrop facies for the samples studied from Inishcorker logs I, II, and III.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Inishcorker Log Number</th>
<th>Facies</th>
<th>Microfacies Description</th>
<th>Appendix 1.9 Plate No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 1.1</td>
<td>I</td>
<td>1</td>
<td>Lenticular laminated, clay-rich, silt-, organic matter-, and fossil-bearing mudstone</td>
<td>1</td>
</tr>
<tr>
<td>IC 2.1</td>
<td>II</td>
<td>1</td>
<td>Laminated and slightly bioturbated, organic matter-rich, silt-bearing mudstone</td>
<td>2</td>
</tr>
<tr>
<td>IC 2.4</td>
<td>II</td>
<td>2</td>
<td>Laminated, organic matter-rich, silt-bearing mudstone</td>
<td>3</td>
</tr>
<tr>
<td>IC 2.5</td>
<td>II</td>
<td>1</td>
<td>Wavy to lenticular laminated, silt-, organic matter-, and clay-pellet–bearing mudstone</td>
<td>4</td>
</tr>
<tr>
<td>IC 2.6 c</td>
<td>II</td>
<td>1</td>
<td>Bioturbated, relic wavy and lenticular laminated, silt-rich, pellet and organic matter-bearing mudstone</td>
<td>5</td>
</tr>
<tr>
<td>IC 3.2</td>
<td>III</td>
<td>2</td>
<td>Laminated, organic matter-rich, clay-pellet-, and silt-bearing mudstone</td>
<td>6</td>
</tr>
<tr>
<td>IC 3.3</td>
<td>III</td>
<td>1</td>
<td>Wavy laminated, silt-, pellet-, and organic matter-bearing mudstone</td>
<td>7</td>
</tr>
<tr>
<td>IC 3.4</td>
<td>III</td>
<td>1</td>
<td>Bioturbated, relic wavy to lenticular laminated, silt-rich, organic matter-, and clay-bearing mudstone.</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4.7: Mudstone microfacies summary for Inishcorker logs I, II, and III.

4.3.3.2: Inishcorker log IV

Thin section analysis – Inishcorker Log IV

A summary table indicating the mudstone microfacies assigned to each of the 14 thin sections is presented below (table 4.8). For a full description of each thin section please see the appropriate plate in appendix 8.
| Sample ID | Facies | Microfacies description | Appendix 4.16 Plate #:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 4.1</td>
<td>2</td>
<td>Thinly laminated, calcite-, silt-, and organic matter- bearing mudstone</td>
<td>9</td>
</tr>
<tr>
<td>IC 4.2</td>
<td>1</td>
<td>Laminated, clay-pellet-, silt-, and organic matter bearing mudstone</td>
<td>10</td>
</tr>
<tr>
<td>IC 4.3</td>
<td>1</td>
<td>Bioturbated, wavy laminated, clay-rich, silt-, and organic matter- bearing mudstone</td>
<td>11</td>
</tr>
<tr>
<td>IC 4.4</td>
<td>2</td>
<td>Wavy laminated (possibly slightly bioturbated), clay-rich, organic matter-, micro and macrofossil-, and silt-bearing mudstone</td>
<td>12</td>
</tr>
<tr>
<td>IC 4.5</td>
<td>2</td>
<td>Thickly laminated, clay-, organic matter, and silt-bearing mudstone</td>
<td>13</td>
</tr>
<tr>
<td>IC 4.6</td>
<td>1</td>
<td>Thickly laminated, clay-, organic matter, and silt-bearing mudstone</td>
<td>14</td>
</tr>
<tr>
<td>IC 4.7</td>
<td>1</td>
<td>Wavy laminated to lenticular laminated, organic matter-rich, silt-, and clay- bearing mudstone</td>
<td>15</td>
</tr>
<tr>
<td>IC 4.8</td>
<td>1</td>
<td>Laminated (?), organic matter-rich, silt-, and clay-bearing mudstone.</td>
<td>16</td>
</tr>
<tr>
<td>IC 4.9</td>
<td>2</td>
<td>Thickly laminated or thinly bedded (?) clay-rich, microfossil-, and silt-bearing mudstone.</td>
<td>17</td>
</tr>
<tr>
<td>IC 4.10</td>
<td>1</td>
<td>Wavy laminated and pelleted, organic matter-rich, silt-, and clay-bearing mudstone.</td>
<td>18</td>
</tr>
<tr>
<td>IC 4.11</td>
<td>1</td>
<td>Wavy laminated and pelleted, organic matter-rich, silt-, and clay-bearing mudstone</td>
<td>19</td>
</tr>
<tr>
<td>IC 4.12</td>
<td>1</td>
<td>Wavy laminated and pelleted, clay-rich, silt- and organic matter-bearing mudstone</td>
<td>20</td>
</tr>
<tr>
<td>IC 4.13</td>
<td>2</td>
<td>Laminated, silt-, clay-, and organic matter-bearing mudstone</td>
<td>21</td>
</tr>
<tr>
<td>IC 4.14</td>
<td>1</td>
<td>Wavy to lenticular laminated, silt-, and organic matter-bearing mudstone.</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 4.8: Inishcorker log IV mudstone microfacies summary.

4.2.3.3: Mudstone Microfacies Types

For facies one and two, identified on Inishcorker, the microfacies identified can be grouped according to which outcrop facies that sample came from. Furthermore, within each facies more microfacies were identified. In facies one, three broad microfacies were identified.

Based on fabric and main components the three broad microfacies types are:

1. Wavy to lenticular laminated, silt-, clay-, calcite-cement, pellet- and organic matter-bearing mudstone
2. Bioturbated, relic laminated clay-rich to silt-rich mudstone
3. Laminated, dark, strongly organic matter-bearing to organic matter-rich mudstone

For facies two, two broad microfacies were identified.

4. Laminated, dark, and organic matter-rich
5. Thinly to thickly laminated with moderate amounts of organic matter and silt

Table 4.9 below lists all of the samples from lithofacies one, along with the corresponding microfacies type (either 1, 2, or 3 from above) and the TOC (Wt %) value for that sample.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample’s microfacies description</th>
<th>Microfacies type</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 1.1</td>
<td>Laminated, fossil-, silt-, calcite-cement-, and organic matter-bearing</td>
<td>1</td>
<td>2.41</td>
</tr>
<tr>
<td>IC 2.1</td>
<td>Laminated and slightly bioturbated, organic-matter-rich, silt-bearing mudstone</td>
<td>3</td>
<td>6.01</td>
</tr>
<tr>
<td>IC 2.5</td>
<td>Wavy to lenticular laminated, silt-, organic matter, and pellet-bearing mudstone</td>
<td>1</td>
<td>3.95</td>
</tr>
<tr>
<td>IC 2.6 c</td>
<td>Bioturbated, relic wavy and lenticular laminated, silt-rich, pellet and organic matter bearing mudstone</td>
<td>2</td>
<td>3.25</td>
</tr>
<tr>
<td>IC 3.3</td>
<td>Wavy laminated, silt-, pellet-, and organic matter-bearing mudstone</td>
<td>1</td>
<td>3.61</td>
</tr>
<tr>
<td>IC 3.4</td>
<td>Bioturbated, relic wavy to lenticular laminated, clay-rich, organic matter-, and silt-bearing mudstone</td>
<td>2</td>
<td>2.68</td>
</tr>
<tr>
<td>IC 4.2</td>
<td>Laminated, organic matter-rich, clay-pellet-, and silt-bearing mudstone</td>
<td>3</td>
<td>4.86</td>
</tr>
<tr>
<td>IC 4.3</td>
<td>Bioturbated, wavy laminated, clay-rich, silt-, and organic matter-bearing mudstone</td>
<td>2</td>
<td>0.80</td>
</tr>
<tr>
<td>IC 4.6</td>
<td>Thickly laminated, clay-, organic matter, and silt-bearing mudstone</td>
<td>3</td>
<td>3.81</td>
</tr>
<tr>
<td>IC 4.7</td>
<td>Wavy laminated to lenticular laminated, organic matter-rich, silt-, and clay-bearing mudstone</td>
<td>1</td>
<td>4.32</td>
</tr>
<tr>
<td>IC 4.8</td>
<td>Laminated (?), organic matter-rich, silt-, and clay-bearing mudstone</td>
<td>3</td>
<td>5.90</td>
</tr>
<tr>
<td>IC 4.10</td>
<td>Wavy laminated and pelleted, organic matter-rich, silt-, and clay-bearing mudstone</td>
<td>1</td>
<td>4.56</td>
</tr>
<tr>
<td>IC 4.11</td>
<td>Wavy laminated and pelleted, organic matter-rich, silt-, and clay-bearing mudstone</td>
<td>1</td>
<td>8.16</td>
</tr>
<tr>
<td>IC 4.12</td>
<td>Wavy laminated and pelleted, clay-rich, silt- and organic matter-bearing mudstone</td>
<td>1</td>
<td>2.57</td>
</tr>
<tr>
<td>IC 4.14</td>
<td>Wavy to lenticular laminated, silt-, and organic matter-bearing mudstone</td>
<td>1</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Table 4.9: Correlation of microfacies from each thin section and the three main microfacies type.
The table below lists the samples from lithofacies two, along with the corresponding microfacies type (either 4 or 5 from above) and the TOC (Wt %) value for that sample:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample’s microfacies description</th>
<th>Microfacies type</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 2.4</td>
<td>Laminated, organic matter-rich, silt-bearing mudstone</td>
<td>4</td>
<td>6.78</td>
</tr>
<tr>
<td>IC 3.2</td>
<td>Laminated, organic matter-rich, clay-pellet, silt-(including microplankton-silt)-bearing mudstone</td>
<td>4</td>
<td>8.21</td>
</tr>
<tr>
<td>IC 4.1</td>
<td>Thinly laminated, calcite-, silt-, and organic matter-bearing mudstone</td>
<td>5</td>
<td>2.34</td>
</tr>
<tr>
<td>IC 4.4</td>
<td>Wavy laminated (possibly slightly bioturbated), clay-rich, organic matter-, micro and macrofossil-, and silt-bearing mudstone</td>
<td>5</td>
<td>3.16</td>
</tr>
<tr>
<td>IC 4.5</td>
<td>Thickly laminated, clay-, organic matter, and silt-bearing mudstone</td>
<td>5</td>
<td>3.37</td>
</tr>
<tr>
<td>IC 4.9</td>
<td>Thickly laminated or thinly bedded (?) clay-rich, microfossil-, and silt-bearing mudstone</td>
<td>5</td>
<td>0.24</td>
</tr>
<tr>
<td>IC 4.13</td>
<td>Laminated, silt-, clay-, and organic matter-bearing mudstone</td>
<td>5</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Table 4.10: Microfacies types from facies two.

Microfacies type 1:

Microfacies type 1 had a wavy to lenticular laminated fabric, with common carbonate cemented laminations identified optically (Fig 4.15) and through BSE (Fig. 4.16). Silt and clay-grade detrital quartz is common and clay minerals are abundant. The TOC ranged from moderately low to high (2.41 – 8.16 Wt %) but average TOC of this microfacies type is good (4.01 Wt%).

Microfacies type 2:

Microfacies type two was characterised by bioturbation and lower TOC values. TOC ranged from 0.80 to 3.25 with an average of 2.24 Wt %. The burrows show preferential cementation (Fig. 4.17 and Fig. 4.18) interpreted to be carbonate cementation. All three samples in this microfacies type come from the more indurated and better-cemented non-fissile horizons of facies one.
Microfacies type 3:

Microfacies type 3 (Fig. 4.19 and 4.20) was characterised by laminated microfacies that showed a variation in organic matter and TOC (3.81 – 6.01 wt %) but with an average TOC that was good to high (5.15 wt %). Quartz silt and quartz overgrowth cement is common, and carbonate cement is present along fractures (Fig. 4.20). Clay minerals are common and their higher reflection coefficient in BSE images would suggest they are dominated by illite (pers. com Taylor, 2012).

Microfacies type 4:

This is the first microfacies type from lithofacies two and it was characterised by its organic matter-rich nature observed optically and through BSE (Fig. 4.21 and 4.22). Optically the thin sections were very dark (Fig. 4.21) yet without magnification some lamination was visible. The BSE images (Fig. 4.22) show abundant quartz silt, which mostly resembled microfossil, with areas of quartz cement overgrowth. Clay and carbonate minerals are uncommon and pyrite is common. Microfacies four had the highest average TOC of all the microfacies from Inishcorker at 7.50. However this microfacies consisted of only two samples (IC 2.4 and IC 3.2), and originated in lithofacies two which had a reduced thickness compared to lithofacies one.

Microfacies type 5:

Microfacies type 5 (Fig. 4.23) was only differentiated from microfacies type 4 by its lower organic matter content, TOC and lighter colour thin section in which both thick and thin laminations were visible (Fig. 4.16). The TOC ranged from 0.24 to 3.37 Wt % and with 5 samples the average was 2.31 %. The samples showed varying amounts of clay and silt, with some being silt-rich and other having common clay-pellets (Fig. 4.23). No bioturbation was observed in these samples.
Figure 4.15: Overview of samples corresponding to microfacies type 1 – wavy to lenticular laminated, silt-, clay-, carbonate-cement-, and organic matter-bearing mudstone. A and B) IC 1.1, green arrows point to silt and clay filled lenses or pellets, yellow arrow points to a possible flattened algal cyst, higher power magnification of a fossil vug in B. C) IC 2.5 showing wavy laminations with light coloured carbonated cemented laminations (yellow arrow) and dark coloured clay and organic matter-rich laminations. D) Scale is same as C, IC 3.3 shows similar carbonate-cemented laminations (yellow arrow) as IC 2.5, with alternating darker laminations. Green arrow shows a quartz silt and clay rich collection of pellets, red arrow points to a carbonate fossil forming a micro-concretion. E) IC 4.4 low power view of general wavy laminated fabric. F) High power magnification of IC 4.14 showing wavy contact between lighter and darker laminations (red dashed line), and an example of the abundant quartz silt and clay rich lens is highlighted (green arrow).
Figure 4.16: BSE images of microfacies I type thin sections. A) IC 1.1 with carbonate-cement (yellow arrow) around carbonate clast of fossil (partially pyritized). Green arrows shows an example of framboidal pyrite. B) Higher power view of IC 1.1, showing carbonate-cement (green arrow) either side of a fracture, and pyrite framboids of various µm sized (yellow arrow). Red arrow shows lath-shaped clay minerals, which were abundant in groundmass. Quartz (Q) grains were common and were both silt–sized and clay-sized. C) IC 2.5 clay-rich with calcite and quartz, and carbonate cement (C). D) IC 3.3 abundant carbonate cement (C) laminations, with quartz (Q) and some clay in groundmass.
Figure 4.17: Thin sections of samples from microfacies 2 – boturbated, relic laminated, clay-rich to silty-rich mudstone. A and B) IC 2.6c, burrows with silt and clay-grade fill of light-coloured minerals (quartz and clay minerals), and darker more organic and clay-rich areas with occasional clay pellets. C and D) IC 3.4, burrows again have a lighter colour fill, relic lamination can be seen with alternating organic-rich and clay-rich laminations. D is a close up of a “pelletoidal” (Seilacher, 2004, p.54) burrow fill, typical of the Ophiomorpha ichnospecies. E and F) IC 4.3, Burrows with a dark clay fill in a matrix of clay and patchy light-coloured cementation, possibly a carbonate.
Figure 4.18: BSE image of microfacies type 2 thin sections. A and B) IC 2.6c, A shows abundance of carbonate cementation and grains at low power. Large siderite (S) grain in B, with carbonate (C) cement and smaller grains, quartz (Q) is common, as is clay (yellow arrow).
Figure 4.19: Examples of thin sections from microfacies type 3 – laminated, dark, strongly organic-bearing to organic-rich mustone. A and B) IC 4.2, hint of lamination is visible at low power in A. B illustrates the very dark, organic-rich fabric, and presence of abundant silt and occasional microfossil (yellow arrow – partially pyritized microfossil, possibly a foraminifera). C) IC 4.6, hint of lamination is visible and best seen towards the bottom of the slide. D) IC 4.8, medium power view highlights the abundant organic matter and common silt grains. The silt included detrital quartz and calcite and microfossils such as sponge spicules (red arrow).
Figure 4.20: BSE images of sample IC 2.1 from microfacies type 3 (facies one). A) Abundant quartz silt (some examples marked by “Q”), with overgrowth of quartz cement visible around some larger grains (see the example highlighted by the green dashed line). Yellow arrows highlight examples of clay minerals (in this case the higher reflection co-efficient indicates illite). Organic matter (OM) is dispersed throughout the sample. B) Note the abundance of quartz in the groundmass, with some clay minerals. The area around the fracture is preferentially cemented by a carbonate (C) mineral and there are also rare carbonate minerals in the groundmass.
Figure 4.21: Example of microfacies type 4(facies two) – laminated, dark, and organic matter-rich. A and B) IC 2.4, very dark, organic matter-rich slide, with organic matter dispersed throughout the slide and abundant silt. B shows a high power view of the dark, organic-rich fabric and a very fine sand (yellow arrow) clast. This clast had like spiny processes on its outer surface and may be a silicified microfossil (possibly a radiolarian). The orange-brown (green arrow) clast may be a phosphate.

Figure 4.22: BSE images of thin sections from microfacies type 4. A and B) IC 2.4, quartz-rich with some carbonate grains (including siderite (S)), clay minerals (green arrow), carbonate cement (C), and common framboidal pyrite (P). Organic matter is dispersed throughout (black areas) in A and B. The black area in the left of B is a fracture. C and D) IC 3.2, is again quartz-rich with abundant organic matter dispersed throughout.
Figure 4.23: Examples of thin sections from microfacies type 5 – thinly to thickly laminated with moderate amounts of organic matter and silt. A and B) IC 4.1, thinly laminated with alternating organic matter-rich layers and silt and clay mineral-rich layers. Some organic matter particles resemble large woody material fragments (red arrow, B). C and D) IC 4.5, thickly laminated, with more organic matter and clay than IC 4.1. E and F) IC 4.13, Lamination thickness was more variable in IC 4.13, with both thick and thin laminations, but this slide was similar in overall nature to IC 4.5, being strongly clay and organic matter-bearing. Organic matter is concentrated in some laminations (darker) but also dispersed throughout the slide (F). Clay pellets are common also (yellow arrow in F), with rare fossil fragments or carbonate grains (green arrow in F).
4.2.4: Spectral Gamma Radiation Analysis

A spectral gamma ray log was conducted alongside Inishcorker log IV, and covering approximately the first 104 m of the 115 m in the sedimentary log. The values recorded in the field for K (%), U (ppm), and Th (ppm) have been converted to API units as described under methods in chapter one (section 1.3.3). The sum of the contribution of each element in API units was calculated to give the standard gamma ray (SGR), which is essentially a total count of the gamma radioactivity of a rock (Rider and Kennedy, 2011, p. 124).

4.2.4.1: Inishcorker log IV

The spectral gamma radiation log (Fig. 4.24) has been shown alongside the sedimentary log to display not just the change in gamma radiation emitted over the length of the log but also the change in the contribution of each element (U, Th, K) to the radiation detected.

The SGR (grey line and shaded area, Fig. 4.24) has an irregular trend but is usually within the range of approximately 150 to 200 API. This is above the “average shale” value of 100 API (Rider and Kennedy, 2011, p. 131). Large variations above and below this range occur, and one in particular spikes to approximately 500 API at approximately 97 m. This spike shows a corresponding spike in U, and a slight drop in K and Th.

Overall the SGR trend appears visually to be more closely related to the U trend than the Th or K trends, as can be expected by the obviously higher contribution of U to the SGR than K or Th (Fig. 4.24).

The authigenic or excess U proportion of a mudstone can be estimated by analysing the Th/U ratio. A Th/U ratio of 3 is representative of a mudstone with a mostly detrital U signature (Wignall & Myers, 1988; Rider & Kennedy, 2011). The Th value in ppm is then divided by the Th/U ratio of 3 (equation 2) to give the normal or detrital U content. The surplus or shortfall in U (equation 3) is then determined by subtracting this normal U value from the U value in ppm (Myers & Wignall, 1987; Rider & Kennedy, 2001).

\[
\begin{align*}
(1) \quad & \text{Th/U} = 3 \\
(2) \quad & \text{Th (ppm from log) } / 3 = \text{U normal (ppm)} \\
(3) \quad & \text{U log } - \text{U normal } = \text{U excess (ppm units, positive for surplus, negative for shortfall)}
\end{align*}
\]

For Inishcorker log IV only 3 readings out of 85 in the spectral gamma ray log showed a negative U excess value. The median U excess value for this log was 9.7, meaning that there was 9.7 ppm more uranium than the Th content would indicate (Myers & Wignal,
1987). The reason for this excess or authigenic U, is however unclear. Areas with excess U often have high TOC values (Rider and Kennedy, 2011), so an attempt was made to see if there was a correlation between TOC and Uranium on Inishcorker.

Three of the ways in which uranium from sea water can be taken up by sediments as outlined by Serra (1979), have been summarised by Rider and Kennedy (2011):

1) Under acidic, reducing conditions, uranium can precipitate from sea water and be deposited with the sediments
2) By attaching or “adsorption” (Rider and Kennedy, 2011) onto the surface of organic matter
3) As uranium found within phosphatic rocks.

Rider and Kennedy (2011) suggest that adsorption of uranium onto the surface of organic matter is likely the more frequent method. The high U contribution of the spectral gamma ray log associated with Inishcorker log IV (section 4.3.5) and the calculated excess U indicate the Clare Shale Formation at Inishcorker should have a high organic matter content (Rider and Kennedy, 2011). This was found to be the case (table 4.8). However, when a cross plot of U values and the corresponding TOC values from the same area was performed, there was no correlation between the two and the coefficient of determination was zero.

The spectral gamma ray profile was also used to make an estimation of the clay mineral content. A Th/K ratio of 4 to 6 is considered normal for mudstones, with lower ratios indicating a higher K and illitic composition, and higher ratios indicating a lower K and a kaolinite composition (Rider and Kennedy, 2011). The modal Th/K ratio of the spectral gamma profile from Inishcorker log IV was 8 and this would indicate that kaolinite dominates the clay fraction.
Figure 4.24: Inishcorker log IV with spectral gamma ray and TOC content.
4.2.5: XRD

Five samples from Inishcorker Log IV were analysed using XRD: IC 4.1, 4.3, 4.8, 4.10 and 4.12. These samples were selected at random and represent, microfacies 5, 2, 3, 1, and 1 respectively.

**IC 4.1:** Dominated by quartz, dolomite and pyrite, with minor muscovite and microline.

**IC 4.3:** Dominated by quartz, pyrite, clinochlore, with some microcline, pyrite and siderite.

**IC 4.8:** Dominated by quartz, muscovite, microcline, with some clinochlore, pyrite and siderite.

**IC 4.12:** Dominated by quartz, microcline, muscovite, clinochlore, with some siderite and pyrite.

All samples were found to be dominated by quartz with varying amounts of muscovite, microcline, and clinochlore, and lesser amounts of siderite, and pyrite, with only IC 4.1 confirming the presence of dolomite.

Accuracy of the XRD analysis is difficult to determine. The results appear to indicate all samples are quartz-rich and contain carbonate (either as siderite, or as dolomite for IC 4.1). The presence of muscovite recorded may be a result of the presence of illite, which is a muscovite clay mineral (Gharrabi et al, 1998).
4.3: Doon West, Ballybunnion, County Kerry

The Clare Shale Formation at Doon West (Fig. 1.1) is represented by a coastal outcrop, located approximately 1km north of the Ballybunnion, in north County Kerry. Here, a sedimentary log was conducted over approximately 74m (Fig. 4.25). The log had to be completed over 2 days as access can only be gained in a tight window between low and high tides. A spectral gamma ray log was conducted over the bottom and top sections of the log with a break of approximately 24 m representing the middle of the section.

4.3.1: Sedimentary Log and Field Observations

Two lithofacies were observed at the outcrop:

1. A non-fissile, recessed, well-cemented, black mudstone, which exhibited alternating light and dark coloured laminations, pyrite lenses, burrow mottling.
2. A silty, dark-grey to black mudstone, which exhibits mostly flaggy to bedding-parallel parting, with occasional interbedded soft and non-fissile mudstone beds up to 30 cm thick. These soft mudstone beds exhibited deformation in places, with relic laminations often preserved.

Facies one (Fig. 4.27) comprised only 2.98m of the overall log, and was assigned to 3 thin units. The first corresponds to the first unit of the log (Fig. 4.25) and is 85cm thick. The second unit from facies one was 1.07m thick and corresponds to the 9th unit on the log at approximately 55m. The third corresponds to the 12th unit on the log at approximately 71.75m, and measured 1.06m in thickness.

Facies two dominated the logged section (Fig. 4.28 and 4.29). Facies one was differentiated from facies two due to its overall lack of fissility or parting, its dominantly black colour, and its recessed profile.

Laminations were present throughout both facies, being mostly planar, with some wavy ripples, and possibly some starvation ripple laminae. Packages of lamination styles were noticed in both facies (Fig. 4.27 (C &D) and 4.28 (E & F)). Bioturbation was not observed with the eye in facies two. Other sedimentary features observed included load structures, slickensides, eroded goniatite casts.
**Figure 4.25**: Sketch of the Doon West sedimentary log.
Figure 4.26: General outcrop photos from Doon West. The bottom photo shows the contact with the younger Dinantian deep-water Carbonates but it is just below the area logged. The middle photograph is representative of the majority of the lower and middle portion of the log. The top photo is representative of the upper 10m of the log. The yellow arrow in the top photo points to a recessed black clay-dominated mudstone that corresponds an ~1m thick unit on the sedimentary log at approximately 72m (Fig. 4.25).
Figure 4.27: Overview of facies one from the Doon West sedimentary log. A) Lowermost log unit, dark black, laminated mudstone. B) Unit 9 of the log, found at approximately 55m in the logged sequence, was a black, recessed, laminated mudstone. C) and D) Closer view of the laminations in unit 9, which appeared rich in pyrite. Long thin pyrite lenses were common (D). Note the colour change towards the top in D, where pyrite-rich laminations are abundant. E) and F) Unit 12 of the log, the second last unit, located at approximately 71.75m, was a recessed, black, laminated mudstone, which also exhibited pyrite-rich laminations and pyrite lenses. (Note the black colour of the freshly exposed surface in E).
Figure 4.28: Overview of facies two from the Doon West sedimentary log.  A) and B) General dark-grey to black, flaggy –parting nature of facies 2.  C) and D) Unit 2 of the log, with the notebook resting on an interbedded, soft, deformed black mudstone bed.  E) and F) Close up of lamination details from approximately 10m into the logged section. Laminations are light in colour, and vary from planar, to wavy, with possible starvation ripples (middle of E). Zones between laminations are dark-grey and massive.
Figure 4.29: Close up of sedimentary details from facies two. A) and B) both from approximately 12m into the logged section. These structures resemble load features, or possible dewatering structures. C) and D) Both from approximately 13m into logged section. These bed surfaces showed linear features that resembled slickensides (yellow arrows in D, plan view).
4.3.2: TOC Analysis

TOC analysis was run for the 15 samples taken from the logged section (Fig 4.25). The results are shown in the table below:

<table>
<thead>
<tr>
<th>ID</th>
<th>wt % TOC</th>
<th>Facies</th>
<th>Overall average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 15</td>
<td>2.47</td>
<td>1</td>
<td>4.47</td>
</tr>
<tr>
<td>NB 16</td>
<td>3.22</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>NB 17</td>
<td>7.18</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 18</td>
<td>6.38</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 19</td>
<td>2.93</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 20</td>
<td>2.16</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 21</td>
<td>5.50</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 22</td>
<td>3.46</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 23</td>
<td>4.68</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 24</td>
<td>5.85</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 25</td>
<td>4.86</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 26</td>
<td>5.91</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 27</td>
<td>6.22</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 28</td>
<td>4.89</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NB 29</td>
<td>1.34</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.11: TOC results for all samples from the Doon West sedimentary log

Four of the above samples are from facies one: NB 15, 16, 26, and 29. TOC results and the average TOC for this facies are displayed in the table below (table 4.12).

<table>
<thead>
<tr>
<th>Facies one</th>
<th>wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 15</td>
<td>2.47</td>
<td>3.23</td>
</tr>
<tr>
<td>NB 16</td>
<td>3.22</td>
<td></td>
</tr>
<tr>
<td>NB 26</td>
<td>5.91</td>
<td></td>
</tr>
<tr>
<td>NB 29</td>
<td>1.34</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.12: TOC results and average TOC for facies one, Doon West.

The remaining eleven samples are from facies two: NB 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 28.

<table>
<thead>
<tr>
<th>Facies two</th>
<th>wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 17</td>
<td>7.18</td>
<td>4.92</td>
</tr>
<tr>
<td>NB 18</td>
<td>6.38</td>
<td></td>
</tr>
<tr>
<td>NB 19</td>
<td>2.93</td>
<td></td>
</tr>
<tr>
<td>NB 20</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>NB 21</td>
<td>5.50</td>
<td></td>
</tr>
<tr>
<td>NB 22</td>
<td>3.46</td>
<td></td>
</tr>
<tr>
<td>NB 23</td>
<td>4.68</td>
<td></td>
</tr>
<tr>
<td>NB 24</td>
<td>5.85</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.13: TOC results and average TOC for facies two, Doon West.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Log facies</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 25</td>
<td></td>
<td>4.86</td>
</tr>
<tr>
<td>NB 27</td>
<td></td>
<td>6.22</td>
</tr>
<tr>
<td>NB 28</td>
<td></td>
<td>4.89</td>
</tr>
</tbody>
</table>

4.3.3: Thin Section and Mudstone Microfacies Analysis

**Facies one:**

For facies one from the sedimentary log (non-fissile, recessed, well-cemented, black mudstone, which exhibited alternating light and dark coloured laminations, pyrite lenses, burrow mottling) 4 thin sections were created and their mudstone microfacies were analysed (table 4.14)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Log facies</th>
<th>Microfacies description</th>
<th>Appendix 1.10 Plate #</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 15</td>
<td>1</td>
<td>Bioturbated, relic laminated, quartz and/or carbonate cement-, silt-, organic matter- and macrofossil-bearing mudstone</td>
<td>1</td>
</tr>
<tr>
<td>NB 16</td>
<td>1</td>
<td>Thickly laminated, silt-, organic matter-, and carbonate cement-bearing mudstone</td>
<td>2</td>
</tr>
<tr>
<td>NB 26</td>
<td>1</td>
<td>Thickly laminated, silt-, organic matter-, carbonate cement, and pellet-bearing mudstone</td>
<td>3</td>
</tr>
<tr>
<td>NB 29</td>
<td>1</td>
<td>Bioturbated, relic laminated, clay-rich, organic matter- and silt-bearing mudstone.</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 4.14: Mudstone microfacies from facies one of Doon West log**

**Facies two:**

For facies two (a dark-grey to black silty mudstone, with flaggy parting, and interbedded thin soft black mudstone beds) the microfacies identified are listed in the table below (table 4.15) along with the relevant plate number in appendix 9. Please refer to the plate for a more detailed description of the samples.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Log facies</th>
<th>Microfacies description</th>
<th>Appendix 9 Plate #</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 17</td>
<td>2</td>
<td>Laminated, organic matter-rich, pellet- and carbonate cement-bearing mudstone</td>
<td>5</td>
</tr>
<tr>
<td>NB 18</td>
<td>2</td>
<td>Thickly laminated, organic matter-rich, carbonate cement-, silt-, microfossil-, and pellet-bearing mudstone</td>
<td>6</td>
</tr>
<tr>
<td>NB 19</td>
<td>2</td>
<td>Bioturbated, relic-laminated, carbonate cement-, clay-, and silt-, bearing</td>
<td>7</td>
</tr>
</tbody>
</table>
After identifying the microfacies for the 4 samples from facies one, it was decided that they could be grouped into two distinct microfacies types:


The microfacies from facies two described above in table (table 4.15) can be grouped into three general microfacies types:

3. Laminated to thickly laminated, organic matter-rich, silt-, pellet-, and/or carbonate cement-bearing mudstone.

The following table (4.16) gives a summary of the samples, the microfacies type it was assigned to and its corresponding TOC:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Microfacies Type</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 20</td>
<td>Bioturbated, relic-laminated, carbonate cement-, clay-, and silt-, bearing mudstone</td>
<td>7</td>
</tr>
<tr>
<td>NB 21</td>
<td>Thickly laminated, organic matter-rich, silt-, and pellet-bearing mudstone</td>
<td>8</td>
</tr>
<tr>
<td>NB 22</td>
<td>Wavy laminated, carbonate-rich, organic matter-, pellet-, silt-, and fossil fragment-bearing mudstone</td>
<td>9</td>
</tr>
<tr>
<td>NB 23</td>
<td>Wavy laminated, carbonate-rich, organic matter-, pellet-, silt-, and fossil fragment-bearing mudstone</td>
<td>9</td>
</tr>
<tr>
<td>NB 24</td>
<td>Thickly laminated, organic matter-rich, silt-, pellet-, and microfossil-bearing mudstone</td>
<td>10</td>
</tr>
<tr>
<td>NB 25</td>
<td>Thickly laminated, organic matter-rich, silt-, pellet-, and microfossil-bearing mudstone</td>
<td>10</td>
</tr>
<tr>
<td>NB 27</td>
<td>Thickly laminated, organic matter-rich, silt-, pellet-, and microfossil-bearing mudstone</td>
<td>10</td>
</tr>
<tr>
<td>NB 28</td>
<td>Thickly laminated, organic matter-rich, silt-, pellet-, and microfossil-bearing mudstone</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 4.15: Mudstone microfacies descriptions for facies two, Doon West.

Mudstone microfacies types:

After identifying the microfacies for the 4 samples from facies one, it was decided that they could be grouped into two distinct microfacies types:


The microfacies from facies two described above in table (table 4.15) can be grouped into three general microfacies types:

3. Laminated to thickly laminated, organic matter-rich, silt-, pellet-, and/or carbonate cement-bearing mudstone.

The following table (4.16) gives a summary of the samples, the microfacies type it was assigned to and its corresponding TOC:
<table>
<thead>
<tr>
<th>ID</th>
<th>Wt % TOC</th>
<th>Log facies</th>
<th>Microfacies type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 15</td>
<td>2.47</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NB 16</td>
<td>3.22</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>NB 17</td>
<td>7.18</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 18</td>
<td>6.38</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 19</td>
<td>2.93</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>NB 20</td>
<td>2.16</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>NB 21</td>
<td>5.50</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 22</td>
<td>3.46</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>NB 23</td>
<td>4.68</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>NB 24</td>
<td>5.85</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 25</td>
<td>4.86</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 26</td>
<td>5.91</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>NB 27</td>
<td>6.22</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 28</td>
<td>4.89</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>NB 29</td>
<td>1.34</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 4.16 Summary of microfacies types for Doon West.*

**Microfacies type 1:**

Microfacies type 1 was characterized by a bioturbated fabric, which exhibited some relic lamination. The silt content varied between the two samples with NB 29 being more clay-rich. NB 29 exhibited mostly horizontal burrows with one large (approximately 3cm) vertical burrow. The BSE images illustrated that NB 15 was silt-rich with common clay (Fig. 4.30), whilst NB 29 was more clay-rich with very fine grained quartz silt. NB 15 showed evidence of quartz cement overgrowth, whilst NB 19 did not. Siderite grains were common in NB 29.

<table>
<thead>
<tr>
<th>Microfacies type 1</th>
<th>Wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 15</td>
<td>2.47</td>
<td>1.91</td>
</tr>
<tr>
<td>NB 29</td>
<td>1.34</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.17: Microfacies type 1, Doon West, average TOC*

**Microfacies type 2:**

Microfacies type two (Fig. 4.31) was characterised by a thickly laminated fabric of alternating silt-rich and clay-and organic matter-rich laminations. Occasional carbonate cemented lenses were present. The silt fraction of NB 16 appeared to be dominated by altered carbonate grains. NB 26 showed abundant very round, carbonate silt, which resembled microfossils (e.g. coccolithophores).
### Microfacies type 2

<table>
<thead>
<tr>
<th>Microfacies type 2</th>
<th>Wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 16</td>
<td>3.22</td>
<td>4.56</td>
</tr>
<tr>
<td>NB 26</td>
<td>5.91</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.18: Microfacies type 2, Doon West, average TOC*

### Microfacies type 3:

Half of the samples (7) were assigned to microfacies type 3, which consisted generally of thickly laminated, organic matter–rich mudstones with varying quantities of carbonate cement, silt (including microfossil silt), and fecal pellets. Figure 4.32 is characteristic of microfacies type 3 and consists of optical and electron optical (BSE) images from NB 18 (appendix 9 plate 6).

<table>
<thead>
<tr>
<th>Microfacies type 3</th>
<th>wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 17</td>
<td>7.18</td>
<td>5.84</td>
</tr>
<tr>
<td>NB 18</td>
<td>6.38</td>
<td></td>
</tr>
<tr>
<td>NB 21</td>
<td>5.50</td>
<td></td>
</tr>
<tr>
<td>NB 24</td>
<td>5.85</td>
<td></td>
</tr>
<tr>
<td>NB 25</td>
<td>4.86</td>
<td></td>
</tr>
<tr>
<td>NB 27</td>
<td>6.22</td>
<td></td>
</tr>
<tr>
<td>NB 28</td>
<td>4.89</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.19: Microfacies type 3, Doon West, average TOC*

### Microfacies type 4

Two samples from facies two were assigned to microfacies type 4 (Fig. 4.33, table 4.20), which like microfacies type 1, had a bioturbated, relic laminated fabric. It differed however, from microfacies type two as the burrows mostly had a light-coloured mineral fill, interpreted to be a carbonate mineral.

<table>
<thead>
<tr>
<th>Microfacies type 4</th>
<th>wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 19</td>
<td>2.93</td>
<td>2.54</td>
</tr>
<tr>
<td>NB 20</td>
<td>2.16</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.20: Microfacies type 4, Doon West, average TOC*

### Microfacies type 5:

Two samples were assigned to microfacies type 5 (Fig. 4.34, table 4.21) from facies two. Microfacies type 5 was characterized by a wavy laminated fabric, best observed without
magnification. Under transmitted light microscopy its components resembled microfacies type 3, however the BSE images showed that it was rich in carbonate-cement and carbonate silt.

<table>
<thead>
<tr>
<th>Microfacies type 5</th>
<th>wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 22</td>
<td>3.46</td>
<td>4.07</td>
</tr>
<tr>
<td>NB 23</td>
<td>4.68</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.21: Microfacies type 5, Doon West, average TOC*
Figure 4.30: Microfacies type 1, Doon West. A) NB 15, disrupted, relic lamination. B) Magnification of area within red box in A, showing a microfossil silt clast (green arrow), and a fecal pellet (yellow arrow). C) Horizontal and vertical burrow of NB 29. D) Magnification of the area shown in C, showing clay rich matrix and dark-clay filled burrow. E) BSE image of NB 15 with yellow arrows showing examples of quartz silt. This image is quartz rich with common clay (green arrow). The quartz clasts showed quartz cement overgrowth. F) BSE image for NB 29, showing a large siderite (S) clast, with a clay mineral rim (green arrow). This slide was more clay-rich and the quartz silt was smaller with no quartz overgrowths observed.
Figure 4.31: Microfacies type 2, Doon West. A) Low power magnification of NB 16, with yellow dashed lines highlighting the thickly laminated nature. B) Medium power magnification of NB 16. The silt clasts appear to be carbonates, whose irregular outlines may suggest some alteration has occurred. C) Low power view of NB 26. There is a visible difference in the silt content of the laminations (see colour change in middle of photo).
Figure 4.32: Microfacies type 3, Doon West.  A) Low power view of NB 18.  The yellow arrow points to a clay or fecal pellet.  The slide is rich in organic matter, and silt is abundant (as carbonate grains and as microfossils or macrofossil fragments).  B) High power view of the nature of the silt fraction.  The yellow arrow points to an example of a microfossil or macrofossil fragment (e.g. sponge spicule, or radiolarians).  C) and D) BSE images of NB 18 show that it is carbonate-rich and clays are not common.  This was not obvious from optical examination in transmitted light.  (C= carbonate, OM = organic matter, F = fracture).
Figure 4.33: Microfacies type 4, Doon West. A) and B): low and high power views of NB 19. Carbonate cemented burrows are observed amongst a clay-rich groundmass in A. The yellow arrow in B points to a crinoid ossicle. C) and D): Low power views of NB 20. The green arrow points to a clay-filled burrow in a carbonate cemented lamination. Carbonate cemented burrows are shown in a dark clay-rich groundmass in D.
Figure 4.34: Microfacies type 5, Doon West. A) Low power view of NB 22. The laminations consisted of alternating silt-rich and less silty laminations. B) Higher power view of NB 22. The yellow arrow points to a lens, interpreted to be a fecal pellet that appears to be carbonate cemented. C) Low power view of NB 23, which was similar in fabric and component parts to NB 22. It also displays a wavy laminated fabric, and contained fossil fragments, pellets, silt and organic matter. D) The BSE image showed that this sample is rich in carbonate silt and cement (C). Possible areas of vuggy porosity (V) are also highlighted.
4.3.4: Spectral Gamma Radiation Analysis

Alongside the sedimentary log, a spectral gamma ray log was conducted, with a 24m break in the spectral gamma ray data in the middle of the section (Fig. 4.35). The SGR was calculated by adding the contributions in API units of U, Th, and K. Figure 4.35 shows that the U trend closely resembles the SGR trend, proving that U is the most significant contributor to the overall gamma radiation of the Clare Shale Formation at Doon West. 

Visual inspection of the log does not suggest a correlation between U and TOC in the bottom half. A slight correlation is indicated in the top section, however when TOC and U are cross-plotted the coefficient of determination ($r^2$) is zero, indicating that there is no correlation between them.

An analysis of the Th/K ratio was conducted in order to learn more about the clay mineral faction. For the 111 spectral gamma ray assay data points, the modal value for Th/K was 7.75. This indicates that kaolinite dominates the clay mineral faction (Rider and Kennedy, 2011).
Figure 4.35: Doon West log, with spectral gamma ray and TOC data
4.3.5: XRD

Five samples were selected at random for XRD analysis. The level of confidence in the results remains uncertain. None of the 5 samples returned any peaks for carbonates minerals yet most samples, both optically and electron optically, display some carbonate, with some being rather carbonate-rich.

Nonetheless the XRD results are presented here as follows:

**NB 15:**
Quartz dominated, with minor peaks interpreted to be muscovite, microcline, and clinochlore.

**NB 18:**
Quartz dominated, with other peaks associated with pyrite, muscovite and microcline.

**NB 21:**
Quartz dominated, with the only other peak assigned to microcline.

**NB 29:**
Quartz dominated, with muscovite, pyrite, microcline, and a minor peak associated with clinochlore.
4.4: St. Brendan’s Well, County Clare

The St. Brendan’s Well (Fig. 1.1) outcrop is located approximately 2 miles outside the town of Lisdoonvarna, in north County Clare. This is an inland stream location, with the outcrop of the Clare Shale Formation forming an approximately 10m high ledge above the top of the Dinantian limestones, over which the stream flows.

The outcrop at this location is very weathered and access to the middle and top of the outcrop is restricted. For this reason, a short log was conducted at the base of the Clare Shale Formation, beginning in a phosphate bed, and another log was conducted towards the top of the outcrop (Fig. 4.36). From these two short logs a composite log was created to represent the outcrop.

Figure 4.36: The outcrop at St. Brendan’s Well. The two portions logged are represented by the white lines and the interpolated areas on the composite log are represented by the dashed white lines.

4.4.1: Sedimentary Log and Field Observations

During a field visit in November 2011 approximately 1.80m was logged at the base of the Clare Shale Formation at this outcrop (Fig. 4.36). The mudstone at the base sits on top of a thin, 5 to 8cm thick pebbly phosphate bed. This phosphate bed sits directly on top of the Dinantian Carbonates. This section logged consisted of dark-grey to black very fissile silty mudstone. The fissility was so strong that no laminations or bedding was observed. It was not possible to make thin sections for the three samples collected from this portion. Due to the unstable nature of the outcrop it was not possible to gain access to the succeeding approximately 4.5m which was interpolated for the composite log (Fig. 4.37). Above this, a further 1.75m was logged (Fig. 4.36), whilst the remaining (approximately 2m) section at the top of the outcrop was also interpolated.
Figure 4.37: Sedimentary log, spectral gamma radiation log and TOC for St. Brendan’s Well, County Clare
Three samples were collected from the lower portion of the log to analyse TOC; one from the phosphate unit (SB 1), and two from the fissile shale above at 50cm intervals (SB 2 and SB 3).

Fissility was less pervasive in the upper logged section with occasional thin (4-10cm) indurated lightly fissile more prominent beds, from which it was possible to take samples for thin sections. These beds often showed laminations on a mm scale.

4.4.2: TOC Analysis

Six samples were analysed for TOC. The first three samples were from the lower portion of the log. SB 1 was taken from the pebbly phosphatic bed. SB 2, and SB 3 were taken from the mudstone of the Clare Shale Formation above the phosphatic bed at intervals of approximately 50 cm (Fig. 4.37). Three samples were also analysed from the top portion of the log, SB 4, SB 5, and SB 6 (bottom to top order).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB 1</td>
<td>0.44</td>
<td>2.92</td>
</tr>
<tr>
<td>SB 2</td>
<td>2.02</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 4.38: Upper portion of the St. Brendan’s Well log.*
4.4.3: Thin Section and Mudstone Microfacies Analysis

Three unusually thin (20µm) thin sections were made for beds from the upper portion of the sedimentary log at a spacing of approximately 50cm (Fig. 4.37). The samples in ascending order are: SB 4, SB 5, and SB 6.

Mudstone microfacies description:

Two microfacies types were identified from the above samples:

1. Lenticular laminated, pellet-rich, carbonate cement-, fossil-, silt-, and organic matter-bearing mudstone (Fig. 4.39 and 4.40)

Microfacies type 1:

Figure 4.39 shows 3 optical photomicrographs and 2 BSE images from sample SB 4. The lenticular laminated fabric is obvious in A and B. The lenticular laminations consists of lenses, interpreted to be fecal pellets, enclosed in a groundmass of dark brown and black clay and organic matter. In A the green arrows point to examples of fecal pellets, whilst the red arrow points to an example of a macrofossil (gastropod). B is a magnification of image A. Image C, although very dark in colour, shows 3 large macrofossil fragments (top and bottom), that each measure > 1mm. Image D (high power BSE image) shows that the sample is actually rather clay-rich (yellow arrows point to examples of lath shaped clay minerals). There is also abundant quartz (Q) and carbonate (C) silt. Image E is a low power BSE image that shows carbonate cement-rich lenses (green arrows), and a large muscovite clast (yellow arrow). The TOC for this sample is 3.18 wt %.
Figure 4.39: Microfacies type 1 – sample SB4. A, B, and C are optical photomicrographs. D and E are electron optical (BSE) images.
Figure 4.40: Microfacies type 1 – sample SB 5. A and B are optical photomicrographs. C and D are electron optical (BSE) images.

In Figure 4.40 the lenticular laminated fabric is observable in image A. In a similar fashion to SB 4, it consists of fecal pellets enclosed in a groundmass of dark brown to black clay and organic matter. It is also fossiliferous and examples of macrofossil fragments can be seen in images A and B (green arrows point to some examples). The BSE images (C and D) also revealed that the groundmass is rich in clay minerals (the yellow arrows point to some examples). Quartz (Q) and carbonate (C) is also abundant and pyrite is common (bright white components in C and D). Areas of carbonate cementation (C) are shown in image C. The TOC for this sample is 2.44 wt %.
Figure 4.41: Microfacies type 2 – sample SB 6. A, B, C, and D are optical photomicrographs. E and F are electron optical (BSE) images.

Figure 4.41 shows sample SB 6, which was assigned to its own microfacies type because it was not pellet rich and had a wavy to lenticular laminated fabric. It was also richer in organic matter than samples SB 4 and 5. However, in a similar fashion to microfacies type one, it had abundant carbonate cement, and common macrofossil fragments (images, A, B, and C). A lamination rich in macrofossil fragments is seen in image A (green arrow). Microfossils were common also and also formed one microfossil-rich lamination (image
yellow arrow in images A and D). Fecal pellets were present but rare (green arrow in B). A possible flattened algal cyst (possibly Tasminites) is highlighted by the yellow arrow in B. The TOC of this sample was 6.79 wt %.

<table>
<thead>
<tr>
<th>Microfacies type 1</th>
<th>Wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB 4</td>
<td>3.18</td>
<td>2.81</td>
</tr>
<tr>
<td>SB 5</td>
<td>2.44</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.23: Microfacies type 1 TOC

<table>
<thead>
<tr>
<th>Microfacies type 2</th>
<th>Wt % TOC</th>
<th>Average TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB 6</td>
<td>6.79</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 4.24: Microfacies type 2 TOC

4.4.4: Spectral Gamma Radiation Analysis

A spectral gamma ray log was conducted on a second visit to the outcrop in March 2012. In a similar fashion to the sedimentary log conducted in November 2011, the spectral gamma ray log shown in figure 4.37 was conducted in segments where safe access could be gained (Fig. 4.36) and a composite spectral gamma ray profile was constructed from this data. The samples and spectral gamma ray profile shown in figure 4.37 were collected on separate occasions (November 2011 and March 2012 respectively).

The SGR API generally ranges from 180 to 300 API units, making it higher than that of an “average shale” (Rider and Kennedy, 2011, p. 131).

As the samples and spectral gamma ray log were collected on separate occasions it was decided not to cross-plot U and TOC, as there is a significant amount of error present regarding the exact position of the samples in respect to the individual spectral gamma ray assay data points.

An analysis of the Th/K ratio was conducted in order to learn more about the mineralogy of the clay fraction of the outcrop. The modal Th/K of the 33 assay points was 4.88. When the modal value lies between a range of 4 – 6 then it is difficult to say whether illite or kaolinite dominates the clay fraction, as a value less than 4 is usual for illitic clays and a value greater than 6 is usual for kaolinite clays (Rider and Kennedy, 2011). The BSE images showed a mix of clay minerals.
5.1: Discussion

5.1.1: Shale Gas Potential of the Clare Shale Formation

The Clare Shale Formation has some characteristics which initially give it a favourable potential for shale gas production. Such factors include its, basin wide distribution, significant thicknesses (up to 280m), and consistently good to high TOC values (mostly above 2 wt% TOC). However, the one of the most important factors that affects the potential of a shale gas reservoir is its thermal maturity levels. The thermal maturity database from the literature that was analysed for this project all points to a source rock that is too over-mature, even for dry gas (Clayton et al, 1989; Goodhue & Clayton, 1999; ). This means that the Clare Shale Formation seems unlikely to contain any significant quantities of gas. Basin modelling would suggest that without the input of abnormally high heat flows associated with igneous activity, a sediment column of approximately 4750m of post-Carboniferous sediment was eroded in order to give the thermal maturity values seen at or near the surface today. However, it is possible that high a heat flow associated with advective heating may have caused the organic matter to reach maturity shortly before the deformation associated with the Variscan Orogeny occurred (Fitzgerald et al, 1994). The maturity trend of the Doonbeg #1 well does not increase with depth as one would expect if simple burial and erosion of sediments was the driving force behind thermal maturation (Fitzgerald et al, 1994; Goodhue & Clayton, 1999). Fitzgerald et al (1994) propose that hot fluids may have escaped from the Munster Basin to the south which may have experienced Variscan deformation before the Upper Carboniferous Shannon Basin.

It was decided not to place scientific confidence in the vitrinite reflectance values obtained from samples collected for this research due to their questionable and poorly preserved nature.

A shale gas potential risk map (Fig. 5.2) was created by combining the thickness (Fig. 3.3), depth (Fig. 3.4), TOC (Fig. 3.5), and thermal maturity (Fig. 3.7) contour maps from chapter 3 (a summary of these is provided in Fig. 5.1). Formation thickness and TOC distribution were considered low risk parameters. However, the low risk of these two parameters is overshadowed by the high risk associated with the high thermal maturity values across the basin and the medium to high risk associated with the restriction of suitable present day burial depths for shale gas production to an area around the Doonbeg
A zone of medium to high risk has been assigned to the Clare Shale Formation where it is buried to a depth of more than 500m in the vicinity of the Doonbeg #1 well, because there is a possibility that the high vitrinite reflectance values seen in this well were enhanced locally by faulting at the base of the Clare Shale Formation (Goodhue & Clayton, 1999).
Figure 5.1: Summary of thickness, depth, TOC, and vitrinite reflectance contour maps for the Clare Shale Formation
Figure 5.2: Shale gas potential risk map for the Clare Shale Formation
5.1.2: Sedimentological Processes and Palaeoenvironment

The range of outcrop lithofacies and microfacies types presented in chapter 4 illustrates that the deposition of the sediments of the Clare Shale Formation involved more than just simple suspension fallout in a euxinic environment as has been suggested in the past (e.g. Rider, 1974). Each outcrop studied showed some lithological differences resulting in the identification of separate lithofacies. Evidence of sedimentary structures such as load casts and slickensides was noted at both Inishcorker and Doon West. However, examination beyond the outcrop scale yielded the most detail and showed also that the Clare Shale Formation is not as monotonous as originally presumed (e.g. Collinson et al, 1991).

Analysis of the microfacies types uncovered and their corresponding TOC’s has revealed that multiple sedimentological and environmental processes were involved.

From the three outcrops studied, three main microfacies types are apparent:

1. A wavy to lenticular laminated mudstone with varying TOC values, silt-rich laminations, and other components
2. A bioturbated mudstone with lower TOC values
3. A laminated mudstone with high TOC values

Microfacies type one from Inishcorker and microfacies types one and two from St. Brendan’s Well were very similar in nature and consisted of a wavy to lenticular laminated, silt-, clay-, calcite cement-, pellet-, and organic matter bearing mudstone. The wavy and lenticular laminations consisted of alternating laminations rich in pellets and/or silt with black laminations rich in organic matter. Multiple carbonate silt-rich laminations (Fig. 4.15) were observed. In Hammes et al (2011) study of the mudstone lithofacies of the Haynesville Shale in east Texas and west Louisiana, similar silt-rich laminations have been interpreted to be the result of occasional turbidity currents. This is the interpretation suggested here also. Such mass movement events could have been initiated by storms (Potter et al, 2005). Such storm episodes could re-suspend carbonate material from shallower areas up-dip and transport them deep into the basin (Potter et al, 2005; Hammes et al, 2011). The silt-rich laminations produced by these events would then be buried by sediments deposited during quieter times as pelagic suspension fallout represented by dark organic rich laminations, and by fecal pellet-rich laminations (Fig. 5.3 and 5.4). The alternating black organic rich laminations and silt, clay mineral and pellet-rich laminations suggests that there may have been a high level of organic productivity in the water column on which pelagic organisms fed. It seems that organic productivity was high enough
during deposition of this microfacies for significant amounts of organic matter to reach the sea floor without being consumed. The average TOC for this microfacies (4.01 wt %) also suggests significant amounts of organic matter were preserved. The lack of bioturbation may suggest that either the area at the sediment/water interface was anoxic and inhospitable to benthic organisms, which would in turn also aid organic matter preservation, or that the rate of pelagic sedimentation of pellets and organic matter combined with occasional density or turbidity flows was sufficient enough to prevent colonisation by benthic organisms.

Graham et al (2011) analysed the lithofacies and geochemical variability of Carboniferous mudstones, onshore UK. Their pelleted mudstones closely resemble the lenticular laminated, pellet-bearing mudstones of this study. In their interpretation they explain how benthic and pelagic organisms would consume some organic matter from the water and pass the waste products which would flocculate together in the water column to form fecal pellets (Fig. 5.4). The fecal pellets are then flattened upon compaction during burial into the lens-like pellets seen in the thin sections (Graham et al, 2011). Alternative interpretations of the cause of lenticular lamination have been offered by Schieber et al (2007) and Schieber et al (2010). Schieber et al (2007) propose that clay pellets form as clays in the water column flocculate, with the larger and heavier pellets subsequently sinking to the sea floor. Schieber et al (2010) have reproduced lenticular lamination in flume experiments that resulted from the erosion, transport and subsequent re-deposition of water-rich mud rip-up clasts. The interpretation of Graham et al (2011) remains the preferred interpretation here for the Clare Shale Formation.

TOC varied between these three similar microfacies types from 4.01 wt % for Inishcorker microfacies type one, to 2.81 wt % and 6.79 wt % for St. Brendan’s Well microfacies types one and two respectively. This may be reflected in the amount of pellets seen, as the more strongly pelleted microfacies type one from St. Brendan’s Well showed the lower TOC. It is interpreted here that during the deposition of pellet-rich laminations, a higher concentration of pelagic organisms were available to consume more organic matter, and that the oxygen levels were sufficient enough at the sediment/water interface to oxidise some of the organic matter. This may have been the result of enhanced circulation during periods of more open connection with the open ocean but to prove this would be beyond the scope of the research for this master degree.
Figure 5.3: The origin of silt in deep basinal environments may be the result of transport by density and turbidity currents. 1) Sediment on the shelf is re-suspended and entrained in a density flow as a result of a storm event. 2) The coarser sediments are deposited up-dip and the finer sediments may be transported into the basin. 3) The silt lamination is then covered by the sediments deposited from suspension fallout. Concepts adapted from Potter et al, 2005 and Hammes et al, 2011.

Figure 5.4: Interpretation of lenticular laminated fabric, pellet-bearing mudstone. Modified from Graham et al, 2011.
Bioturbation was obvious in three microfacies, Inishcorker microfacies type two (Fig. 4.17), and Doon West microfacies types one (Fig. 4.30) and four (Fig. 4.33). The presence of bioturbation shows that anoxic conditions were not always present and at times the environment was more oxygenated, making it hospitable to burrowing benthic organisms. Optical and electron optical analysis revealed that the burrows of Inishcorker microfacies type two and Doon West microfacies type four were mostly rich in carbonate cement, whereas Doon West microfacies type one appeared optically to be clay filled. BSE analysis of this microfacies also indicated abundant clay, but quartz silt and quartz cement overgrowths were common also. It has been suggested that the mineralogy indicates proximity to either a carbonate source or a siliciclastic source (Hammes et al, 2011). This may indicate that in general, the basin axis outcrops of Inishcorker and Doon West were more proximal to a carbonate source, such as a carbonate ramp, rather than a siliciclastic source (Hammes et al, 2011). The average TOC values for the bioturbated microfacies were the lowest measured. Much of the organic matter would have been consumed by the fauna or oxidised in the water column or on the sea floor (Potter et al, 2005).

The remaining microfacies types are characterised as laminated (including thickly laminated), organic matter-rich to strongly organic-matter bearing mudstones and being either calcareous or siliceous. These microfacies include, Inishcorker microfacies types three (Fig. 4.19 and 4.20), four (Fig. 4.21 and 4.22), and five (Fig. 4.23), along with Doon West microfacies types two (Fig. 4.31), three (Fig. 4.32), and five (Fig. 4.34). The laminations consisted of alternating dark brown to black clay and organic matter-rich laminations, and lighter coloured silt-rich and sometimes pellet-bearing laminations. This indicates that the sedimentary processes in action involved a combination of pelagic and hemipelagic suspension fallout of organic matter, clay pellets and floccules, and episodic pulses delivering the coarser silt to the basin such as density flows and turbidity currents. These laminated microfacies also showed the higher average TOC values ranging from 2.31 wt % at the lower end to 7.50 wt % at the higher end, with five out of the six microfacies having average TOC values greater than 4 wt %.

Inishcorker microfacies types three, four, and five are dominated by siliceous components and also show evidence of quartz overgrowth cementation. The dominance of siliceous components suggests that these were more proximal to a siliceous source rather than a carbonate source. The silt component of the Doon West microfacies types two, three, and five on the other hand was dominated by carbonates and there was also a strong carbonate cement component. This suggests that Doon West was more proximal to a carbonate
source. This variation between carbonate components and siliceous components may indicate that the basin had both a siliciclastic slope and shelf with a shallower carbonate source even further up-dip such as a carbonate platform. On the other hand it could be a reflection on the stratigraphic intervals logged and sampled. The Doon West log was conducted near the base of the Clare Shale Formation, just above the contact with the Dinantian carbonates below. The abundance of carbonate components in the Doon West log may indicate that as the basin became deeper at the start of the Namurian, the carbonate factories in shallower waters up-dip where able to keep up with sea-level rise for a time and provide carbonate sediments to the deeper parts of the basin. The Inishcorker log on the other hand was located further up section from the carbonates below, and rising sea levels and sea level high stand conditions may have shut down any carbonate factories leading to the dominance of siliceous components at Inishcorker.

5.1.3: Suitability as a Shale Gas Reservoir

Although the high thermal maturities of the Clare Shale Formation indicate it has probably lost any gas it once had, its high TOC content and relatively good thicknesses provide an ideal opportunity to study source rocks in more detail, particularly on a microscopic level. Most of the microfacies uncovered over the course of the research for this master degree have high TOC values, which may suggest that in terms of organic richness the entire formation could be considered as one large continuous sweet spot because high TOC values are linked to porosity and higher gas saturations (Passey et al, 2010). The lower TOC bioturbated microfacies are confined to small, well-cemented horizons, which have been interpreted here to have a negligible effect on the overall TOC distribution of the formation.

Another factor that is essential for consideration in determining shale gas reservoir suitability is the fracability of the formation. This refers to how effectively artificially induced fractures will propagate through the formation. Clays behave more plastically than brittle minerals such as carbonates and quartz, and are therefore less favourable for hydraulic fracturing (Passey et al, 2010). Many of the microfacies uncovered in the Clare Shale Formation appear to have a good to considerable amount of both carbonate or quartz components and cements, which increase the brittleness of the formation. Although it was beyond the scope of this research to conduct a quantitative analysis of the mineralogical content of the samples, the optical and electron optical qualitative analysis indicates that the Clare Shale Formation lies below the 50% clay line. Most of the current producing
shale gas formations in the United States are also below the 50% clay line (Passey et al., 2010, Fig. 11).

Figure 5.5: Mineral composition ternary diagram, showing the compositions of the Barnett and Eagleford shale gas reservoirs. From Passey et al, 2010 (Fig. 11).

5.2: Conclusions

The aim of this research master degree was to evaluate the sedimentology of a potential shale gas formation. Although much is known about the palaeontology and biostratigraphy of the Clare Shale Formation, and on the sedimentology of the younger formations that form the Namurian basin fill succession, a detailed study on the sedimentology of the Clare Shale Formation had never been done.

By combining outcrop studies with laboratory analytical techniques a variety of mudstone microfacies types were uncovered and interpreted. The microfacies analysis revealed valuable information that would not be apparent beyond microscope level. Analysis of the types of mudstone fabrics present, the components of the microfacies and their corresponding TOC values led to interpretations of the sedimentary processes active and the environmental conditions at the time of deposition of the Clare Shale Formation.
Sedimentary processes although dominated by suspension fallout, also involved periodic mass movement processes such as turbidity current and debris flows. The environmental conditions and proximity to either a carbonate source or siliciclastic source controlled the composition of the mudstone components. For example, laminated, organic-rich microfacies dominated during times of low oxygenation or anoxia, while pellet-rich lenticular laminated, and bioturbated microfacies occurred during times of increased oxygenation. This shows that there was more involved in the deposition of the Clare Shale Formation than just simple suspension fallout in an anoxic environment. These analytical methods could be applied to other potential shale gas reservoirs to reveal the true nature of their sedimentology also. In particular it could be useful to conduct similar studies on mudstones that have a greater deal of vertical and lateral variability in their organic richness. The variation in depositional environments and sedimentary process will play a part in the distribution of shale gas characteristics across a formation, such as TOC, thickness and mineralogy. Understanding these factors may help to identify sweet spots to target for drilling and production.

It became apparent early on that according to the data available for this research, the Clare Shale Formation had experienced intense heating at some stage in its geological history that had pushed it right through all of the hydrocarbons windows into the over-mature or dead carbon zone. However undesirable this outcome was to the shale gas potential of the formation it did not stand in the way of the attempt to understand more about the sedimentology a formation, that in every other way seemed to be the perfect shale gas reservoir.

5.3: Recommendations

The following recommendations are suggested if this work were to be expanded upon:

A. Conduct further field work, in particular it is recommended to attempt to log an entire section of the Clare Shale Formation from its base to its top. This may be possible in the vicinity of Ballybunnion, County Kerry.

B. Subsequently, it is recommended to attempt to integrate the biostratigraphic framework (that is already in existence) with the sedimentology of the Clare Shale Formation. This would in constructing a basin wide analysis of the Clare Shale Formation. It may also form the basis for chronostratigraphic and sequence stratigraphic work. This would have involved the recognition in the field of the relevant marine bands, along with collecting and identifying many goniatite and
ammonoid fossils. It was beyond the scope and time allocated for this research to assess the biostratigraphy of the Clare Shale Formation.

C. Collaboration with other bodies such as the Geological Survey of Ireland, or Universities in Ireland who have collected core from the basin. This would potentially provide an opportunity to conduct a more in depth thermal maturity analysis, which may give more reliable results than the vitrinite reflectance data collected from outcrops for this research. If petrophysical data was taken alongside the core then this would provide an excellent opportunity to conduct an integrated subsurface description. This is particularly relevant for spectral gamma ray analysis, which is more effective in the subsurface than on weathered outcrops.

D. Assess the 2D seismic data that exists for the onshore basin. This was also beyond the scope of this masters research.

Ambassador Irish Oil Company (1963), Well report Doonbeg No. 1, County Clare, Ireland.


Clayton, G., Haughey, N., Sevastopulo, G.D. and Burnett, R., (1989), Thermal maturation levels in the Devonian and Carboniferous rocks in Ireland, Dublin, Geological Survey or Ireland


References


Heckel, P.H. (2008), "Carboniferous Period". In Ogg, J.G. & Gradstein, F.M. The concise geologic time scale, Cambridge University Press, pp.73-83


Martinsen, O., Lien, T. & Walker, R.G. (2003), "Facies and sequential organisation of a mudstone-dominated slope and basin floor succession: the Gull Island Formation,


**Internet Resources:**

Google (2012), *Google Earth*. Available from:

Petroleum Affairs Division (2012), *Internet Mapping Framework*. Available from: Department of Communications, Energy and Natural Resources Web site:


Appendix 1: Mudstone Microfacies Nomenclature

The nomenclature utilised for this project is based on the system devised by Macquaker and Adams (2003) that allows for a simple and clear classification of mudstone microfacies based on their textural and compositional characteristics. Each sample is assigned a name based on its sedimentary structures and amount of components that comprise more than 10% of the rock.

<table>
<thead>
<tr>
<th>Percentage of component</th>
<th>Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 90 %</td>
<td>Dominated</td>
</tr>
<tr>
<td>50 – 90 %</td>
<td>Rich</td>
</tr>
<tr>
<td>10 – 50 %</td>
<td>Bearing</td>
</tr>
</tbody>
</table>

Mudstone description prefixes (from Macquaker and Adams, 2003).

An example of a rock name using this nomenclature is “silt- and fossil-bearing, clay-rich mudstone” where the rock has between 50 to 90% clay, and contains between 10 to 50% silt, and between 10 to 50% fossil components.

The use of prefixes to clearly demonstrate the texture of the mudstone is encouraged. Examples of prefixes include “bioturbated”, “laminated”, “thin-bedded”, “pelleted”, and “relic-bedded”. An example of a mudstone name using the textural prefix would be: “Bioturbated, silt-rich, calcite-cement-bearing mudstone” (bioturbated, with 50 to 90% silt, and between 10 to 50% calcite-cement).

The fabric of the mudstones seen in the thin sections is described according to the lamination types of O’Brien and Slatt (1990), which is summarised as follows:

<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finely laminated</td>
<td>Laminations &lt; 0.1 mm thick of alternating silt, and clay and organic matter with parallel contacts between laminations.</td>
</tr>
<tr>
<td>Thickly laminated</td>
<td>Similar alternating laminations as finely laminated but laminations are &gt; 0.1 mm</td>
</tr>
<tr>
<td>Wavy laminated</td>
<td>Similar to finely laminated but the contacts between lamina are wavy instead of parallel.</td>
</tr>
<tr>
<td>Lenticular laminated</td>
<td>Pale coloured lenses of quartz, calcite and clay form layers rather than continuous laminations, with lenses surrounded by dark clay and organic matter.</td>
</tr>
</tbody>
</table>


Lenticular lamination is best described by Schieber et al (2010) who describe it as having a “flaser-bedding appearance” and as consisting “of lenses of variable composition that are arranged in wavy layers”.

140
### Appendix 2: Sedimentary Log Key

<table>
<thead>
<tr>
<th>Sedimentary Feature</th>
<th>Key Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay-rich mudstone</td>
<td>**</td>
</tr>
<tr>
<td>Silt-rich mudstone</td>
<td></td>
</tr>
<tr>
<td>Pencil-structure fissility</td>
<td></td>
</tr>
<tr>
<td>Bedding-parallel flaggy fissility</td>
<td></td>
</tr>
<tr>
<td>Horizontal laminations</td>
<td></td>
</tr>
<tr>
<td>Wave ripples</td>
<td></td>
</tr>
<tr>
<td>Heterolithic Unit</td>
<td></td>
</tr>
<tr>
<td>Load casts</td>
<td></td>
</tr>
<tr>
<td>Slickensides</td>
<td></td>
</tr>
<tr>
<td>Mud rip-up clasts</td>
<td>:</td>
</tr>
<tr>
<td>Bioturbation</td>
<td></td>
</tr>
<tr>
<td>Horizontal burrow</td>
<td></td>
</tr>
<tr>
<td>Vertical burrow</td>
<td></td>
</tr>
<tr>
<td>Goniatite</td>
<td></td>
</tr>
<tr>
<td>Concretion</td>
<td></td>
</tr>
<tr>
<td>Plant material</td>
<td></td>
</tr>
<tr>
<td>Unit contacts</td>
<td></td>
</tr>
<tr>
<td>Erosional</td>
<td></td>
</tr>
<tr>
<td>Sharp</td>
<td></td>
</tr>
<tr>
<td>Gradational</td>
<td></td>
</tr>
</tbody>
</table>
A) Black thinly bedded silty mudstone of unit 1 (facies 2), notebook is approximately 20 cm long. B) Upper part of unit 1 showing gradational contact with unit two. C) Black laminated silty mudstone of unit two. Note the difference in fissility/parting style between the two units (and hence between facies 1 and 2). Unit two shows a platy to pencil-structure-like fissility whereas unit 1 shows a flaggy and bedding plane parallel parting. Hammer is approximately 30 cm long. D) Upper portion of unit two. The yellow notebook (20 cm long) is resting on a better-cemented bed and at least 3 can be clearly seen from the photo.
Appendix 1.4: Outcrop photos Inishcorker log IV unit 3

A) Contact between units 2 and 3, unit 3 had a sharp and undulating contact. Note the cast left by erosion of a large concretion at the base of unit 3. Measuring tape scale is approximately 1 m. B) Another large cast left by erosion of a concretion (~ 50 cm in diameter). Note the flaggy parting and the warping of the beds around the former concretions. Notebook for scale is 20 cm in length. C) The gradational contact between units 3 and 4 is seen here where thinly bedded flaggy parting gives way gradually to platy fissility. D) Unit 3 showed a variety of features and this photo shows possible load casts on the surface of a bed. The loading (?) structures were visible on the base of the bed above.
Appendix 5: Outcrop photos IC log IV unit 4

A) Gradational contact between unit 3 and unit 4 (scale 1 m). B) Pyrite rich-lamination and mottled texture in hand sample. C) ~ 1 m thick better-cemented non-fissile bed (notebook for scale in photos C, E, and F is ~ 20 cm long). D) Sample bags in bottom right and middle left mark location of samples IC 4.6 and 4.6 respectively (backpack for scale). C) Sharp upper contact with unit 5. D) Sharp upper contact with unit 5; note the change from platy pencil-structure-like fissility to flaggy parting. E) and F) Contact between unit 4 and 5.
A) Thinly bedded black silty mudstone of unit 5. B) Bed surface with possible load structures (red arrows) and slickensides (green arrow). C) Same bed surface as B. D) Sample IC 4.9 showing load structures on its base (scale ~ 5 cm). E) Bed surface with deformation which resembled wave ripples. Pencil for scale in photos B, C, and D is ~ 15 cm in length, notebook in A is approx 20 cm in length.
A) The nature of unit 6 and facies 1: platy to pencil-structure-like fissile silty mudstone with interbedded non-fissile silty mudstone (pencil sits on non-fissile bed). B) Typical nature of unit 6, dominated by fissile silty mudstone (pencil for scale circled in yellow). C) Unit 6 fines upwards to a 50 cm horizon of clay-rich mudstone (black to red-brown in colour) at the very top of the unit (notebook marks this clay-rich horizon). Pencil and notebook used as scales are 15 cm and 20 cm in length respectively.
Appendix 8:

Plate 1: IC 1.1 (Inishcorker log I)

A: Low power magnification of lenticular laminated, clay-rich, silt-, fossil-, and organic matter-bearing mudstone, with vuggy porosity created by erosion of a shell fragment circled in red, and a fine sand sized sponge spicule in top left.

B: Medium power view shows the lenticular lamination fabric of light-coloured clay-rich lenses enveloped in a matrix of black organic matter.

C: Higher power view of vug enclosed by red circle in A.

D: Higher power magnification of A, with red arrows pointing to possible flattened algal cysts or clay-rich lenses, green arrow points to possible quartz silt-rich-pellet.

E and F: Possible gastropod circled in red, in a clay-rich and calcite cement-bearing matrix (red arrow). Cross polars in F show the abundance of calcite grains filling the gastropod cast.

Mudstone microfacies description:
Lenticular laminated, clay-rich, silt-, organic matter-, and fossil-bearing mudstone.
Plate 2: IC 2.1 Thin Section (Inishcorker log II)

A: Low power view shows wavy to lenticular laminated fabric. The darker laminations are not lenticular but contain a higher proportion of dark clay minerals and organic matter.

B: Medium power view showing the nature of the lenticular laminations and the silt component. Enclosed the red circle is a high relief, clear mineral, which showed bright birefringence colours in crossed polars and is interpreted to be muscovite mica. The silt clast in the green circle is an example of a quartz microfossil e.g. sponge spicule or radiolaria.

C: The laminations can be clearly seen but enclosed within the red box is a zone which shows significant disruption to indicate bioturbation.

D: Zone shown in red box in C under a higher magnification. The disruption of the laminae is obvious and the outline of possible burrows has been suggested.

Mudstone microfacies description:
Thickly to lenticular laminated and slightly bioturbated, organic matter-, and silt-bearing mudstone.
A: Low power view shows abundant silt. The very dark nature of this slide is also apparent.

B: Medium power view of possible microfossil quartz silt (clear) and a possible phosphate clast (orange-brown).

C: Higher magnification of large silt clasts in B. Among the matrix, clay-grade light coloured minerals can be seen (quartz or carbonate) and black organic matter is abundant.

D and F: The red arrows point to clay-filled or cemented fractures.

D and E: The green arrows point to fractures with a partial fill of red/brown round blobs that may be organic matter or residual hydrocarbons.

Mudstone microfacies description:
Laminated, organic matter-rich, silt-bearing mudstone.
A: Low power magnification showing the laminated fabric which is best described as a mixture of wavy and lenticular lamination with light-coloured quartz-rich laminations with undulating wavy contacts and darker laminations that are composed of layers of light-coloured lenses of quartz and/or clay surrounded in a matrix of black organic matter.

B: Medium power magnification of the area enclosed in the red box in A. The red arrow illustrates an example of a lenticular lamination.

C: Medium power view illustrates how some beds are not continuous and pinch out or vary in thickness, which may indicate some rip-up clasts

**Mudstone microfacies description:**

Wavy to lenticular laminated, silt-, organic matter, and pellet-bearing mudstone.
A: low power view illustrating the laminated fabric, and burrows. The darker laminations have a lenticular fabric of light-coloured pellets surrounded by dark clay and organic matter. The lighter coloured, dusty cream laminations have a wavy fabric and are rich in fine silt and clay-grade light mineral, presumably quartz.

B: Medium power magnification of area highlighted in the red box in A, showing the light coloured, fine-grained (clay-grade) mineral burrow fill.

C: Shows bioturbated/burrowed area with pellet-rich lamination beneath.

D: medium power magnification of area highlighted in C.

E: low power view of additional smaller burrows in the foreground, out of view in C and D.
F: Higher power view of nature of clasts in the matrix, the clast enclosed in the red circle is orange-brown in colour, and sub-euhedral in shape, suggesting it may be an autogenic mineral.

Mudstone microfacies description:
Bioturbated, relic wavy and lenticular laminated, silt-rich, pellet- and organic matter-bearing mudstone.
The very dark nature of this slide made it difficult to accurately describe in detail all components, however, enough could be seen to describe the following:

**A:** Low power view shows the dark nature of this sample, however, a thickly laminated fabric (note darker lamination between the green lines) and strong silt-bearing nature are observable. The darker lamination has less silt than the upper and lower lamination and has more black organic matter.

**B:** Medium power view of A, focused on the clear fine sand grain (circled in A), which appears to be a microfossil.

**C:** High power magnification of area in B, shows light coloured clay or quartz lenses or pellets highlighted by the red arrows, and the detail of the microfossil highlighted by the green arrow. This spherical, clear quartz grain appears to have spiny process, suggesting it has a biological affinity.

**Mudstone microfacies description:**
Thickly laminated, organic matter-rich, silt-, and pellet-bearing mudstone.
Plate 7: IC 3.3 Thin Sections

A: Low power view, green box highlights lamination rich in orange-brown silt with some quartz silt (magnified in photo B).

B: Green box shows a orange-brown silt rich continuous lamination, that may be phosphatic grains. These were also found dispersed throughout the slide in a much less concentrated fashion (see yellow arrow in F).

C: Red box highlights quartz silt-rich lamination and lenticular light-coloured (presumably clay-grade quartz) pellet-rich laminations (magnified in both photos C and D). Green box highlights a quartz-silt rich lamination with a possible micro-concretion (red box shows same detail as photo A).

D: Higher power view showing detail of clay-pellet-rich laminations (in photos A and C) enveloped in a matrix of dark clay and organic matter.

E: Higher power view of silt-rich lamination and possible micro-concretion from photo C.
**F:** High power view of nature of silt fraction; mostly quartz silt, blue arrows points to possible microplankton (e.g radiolaria). Yellow arrow points to orange-brown round silt, which may be a phosphate clast?

**Mudstone Microfacies description:**
Wavy laminated, silt-, pellet-, and organic matter-bearing mudstone.
A: Low power view of mottled bioturbation fabric/ (rip-up clasts?) and non-bioturbated lenticular lamination fabric (e.g zone marked by red arrow). Burrows have a mostly fine grained (clay-grade) light coloured mineral fill, possibly a clay mineral or fine grained quartz (see green arrows in D also).

B: Original bedding preserved, with light coloured silt-rich lamination (green arrow), organic matter-rich lamination (blue arrow), and bed with lenticular lamination of light-coloured silt lenses (pellets?) and organic matter (red arrow).

C: Red arrow shows original lamination, rich-in clay fecal pellets. The green arrow is a flattened burrow.

D: Green arrow points to burrow fill which is clay-rich and has a pelleted texture, red arrow points to clay fecal pellet.

Mudstone microfacies description:
Bioturbated, relic wavy to lenticular laminated, silt-rich, organic matter-, and clay-bearing mudstone.
Plate 9 – IC 4.1 (Inishcorker log IV)

Scales in photomicrographs A and B are 2000 µm (2 mm), scales in B and D are 0.5 mm.

A: Low power view (scale 2 mm) showing the thinly laminated fabric of this sample, and the large dark brown fragments of organic matter, possibly woody material.

B: Medium power view of matrix in crossed polars with yellow arrows pointing to some examples of the calcite clasts with high birefringence colours.

C: Low power view (scale 2 mm) showing randomly orientated dark brown organic matter fragments.

D: Medium power magnification of possible woody material fragments enclosed in red circle in C.

**Mudstone Microfacies:**
Thinly laminated, calcite-, silt- and organic matter- bearing mudstone.
A: Low power view of general nature of this organic matter-rich, silt-bearing laminated mudstone.

B: Low power view illustrating the darker lamination running through the middle of the photo. This lamination had less clay-pellets and was richer in organic matter.

C: The red box highlights a possible conodont or other microfossil. The green box highlights an amalgamation of very fine sand grains that show partial pyritization.

D: Medium power magnification of the microfossil in C.

E: Medium power magnification of the pyritized clasts in C.

F: High power magnification of the conodont/microfossil in C and D. This appears to be clear in colour but shows an internal fibrous structure which indicates it may be phosphatic. The yellow arrow points to one example of the many clay-pellets.

**Mudstone microfacies description:**
Laminated, silt-rich, microfossil-, clay-pellet-, and organic matter-bearing mudstone.
A: Low power view showing the wavy lamination fabric of light cream to light brown clay-rich laminations and dark-brown to black organic rich laminations.

B: Low power view illustrating the “mottled” texture that is imposed over the laminated fabric towards the bottom of the slide (see within the zone marked by the yellow line).

C: Medium power magnification of the “mottled” texture, which appears to consist of light cream to brown coloured clay minerals, with possible burrows (yellow arrows) with a dark fill.

D: High power magnifications of the “mottled” area towards the bottom of the slide, also shown are a brown phosphate grain (red arrow) with black organic matter and pyrite dispersed throughout.

**Mudstone microfacies description:**

Bioturbated, wavy laminated, clay-rich, silt-, and organic matter-bearing mudstone.
**Plate 12: IC 4.4 Thin Section**

**A:** Low power view of top of slide, showing almost translucent laminations at the top that are strongly cemented. The cement did not show any birefringence or extinction in cross polars and was not identified. The overall fabric of the slide is one of wavy laminations.

**B:** Low power view of wavy lamination fabric, and occasional silt and very fine sand grains.

**C:** Low power view highlighting possible burrow with dark fill (red arrow) and white macrofossil fragments surrounding it (these are interpreted to be crinoids ossicles or echinoderm plates). The yellow arrow points to a light brown clay-pellet.

**D:** Medium power view of wavy laminations consisting of discontinuous lenses of alternating light brown clay and dark brown to black organic matter and clay. The red arrows point to macrofossil fragments which are possibly echinoderm fragments.
E: Red arrow points to a possible foram (species unidentified) which is almost 1 mm in length. This was located amongst the clear coloured laminations at the top of the slide seen in A.

F: Red arrow points to a macrofossil shell fragment, which showed calcite birefringence colours in cross polars.

**Mudstone microfacies description:**
Wavy laminated (possibly slightly bioturbated), clay-rich, organic matter-, micro- and macrofossil-, and silt-bearing mudstone.
Plate 13: IC4.5 Thin Section

A: Low power view showing thickly laminated fabric of this slide. Arrows point to clay-pellets. Laminations vary in clay content, with the darker laminations having less clay.

B: Medium power view of the fabric of this sample. The laminations consist of various quantities of clay and organic matter. The red arrow points to some calcite silt, although most of the silt was quartz.

Mudstone microfacies description:
Thickly laminated, clay-, organic matter-, and silt-bearing mudstone.
Plate 14: IC 4.6 Thin Section

A: Low power view of sample IC 4.6, showing a thickly laminated fabric, with the darker lamination being more organic rich than the lighter brown laminations. The red arrow points to a possible fossil fragment.

B: Medium power magnification of A, with possible fossil fragment (red arrow).

C: Medium power view showing dark organic matter matrix and an interesting silt grain in red circle.

D: Silt/ very fine sand grain from C in higher power view. This grain was clear in plane polarized light, and clear in crossed polars (although similar grains showed a brown undulose extinction), with a high relief and a cleavage parallel to its long axis. The high relief and cleave suggests it could be a mica but the lack of colour or birefringence colour is puzzling.

Mudstone microfacies description:
Thickly laminated, clay-, organic matter-, and silt-bearing mudstone.
A: Low power view. This sample shows a mixture of both wavy lamination and lenticular lamination. Light coloured cream and light brown silt (possibly quartz mineral) rich lenses (red arrows point to some examples) are surrounded in a matrix of dark clay and organic matter. These lenses form the lenticular lamination seen throughout most of the slide but can be seen concentrated in wavy lamination as in the top of this photo.

B: Another low power view of the wavy laminated to lenticular laminated fabric of this sample.

C: Medium power view with a possible brown-green glauconite grain enclosed in the red circle.

D: Higher power view of possible glauconite grain shown in C. Also highlighted by the red arrow is a light coloured lense, which seems to consist of an amalgamation of many small round quartz grains. It may be a quartz microfossil rich fecal pellet. The colour of the silt fraction is a dusty cream to light brown colour mostly.

**Mudstone microfacies description:**
Wavy laminated to lenticular laminated, organic matter-rich, silt-, and clay- bearing mudstone.
A and B: As one can see this slide was very dark and may have been too thick. Without magnification where was a slight hint of lamination visible with the naked eye but under magnification this was not observable. The slide has a strong silt component (approximately 40 %) and would appear to be rich in organic matter (> 50 %) due to its dark appearance. Dark brown clay comprises the remainder of the matrix and is estimated at approximately 10 %.

C and D: Medium and high power views respectively, illustrating the abundant silt component – which is similar to the previous slide, where the silt is mostly a dusty cream colour to clear and may be mostly quartz.

Mudstone microfacies description:
Laminated (?), organic matter-rich, silt-, and clay-bearing mudstone.
Plate 17: IC 4.9 Thin Section

A: Low power view best illustrates the thickly laminated / thinly bedded nature of this mudstone. The beds internally show a wavy laminated fabric of quartz clay and silt (light coloured) and dark coloured clay and organic matter laminations.

B: Red box encloses a lamination that is rich in microfossil silt, possibly sponge spicules or radiolaria. Bottom shows an interesting zone of organic matter-rich wavy laminations and interlaminated cement layers that showed a chalcedony-like zoned extinction.

C: Red box encloses a medium power magnification of the above mentioned microfossil silt rich lamination.

D: Higher power magnification of the interlaminated organic rich and cement rich zone.

**Mudstone microfacies description:**
Thickly laminated or thinly bedded (?) clay-rich, microfossil-, and silt-bearing mudstone.
Plate 18: IC 4.10 Thin Section

A: Low power view showing a wavy laminated fabric. Red arrow points to a lamination that is rich in quartz silt and clay lenses. The yellow arrows point to isolated quartz and clay lenses. These lenses may be fecal pellets.

B: Low power view of wavy laminated fabric. The red arrow is pointing to pellet rich lamination and the yellow arrow points to an isolated pellet.

C: Medium power view of quartz and clay pellet rich lamination seen in A. The red arrow points to the upper lamination in A. This pellet has an internal structure that resembles an amalgamation of many spherical quartz grains, such as microfossils, and is interpreted to be a micro-fossil rich fecal pellet.

D: High power view of the nature of the matrix, illustrating the clear to cream and light brown silt and dark very fine grained organic matter rich background.

Mudstone microfacies description:
Wavy laminated and pelleted, organic matter-rich, silt-, and clay-bearing mudstone.
Plate 19: IC 4.11 Thin Section

A: This slide is very dark, but laminations can still be seen, and as their contacts are not sharp they are hence described as wavy laminations. Silt is abundant and estimated at 25%.

B: Medium power view area in red box in A. Between the red arrow is a lamination rich in light coloured quartz clay and silt-rich lenses. Yellow arrows show isolated similar lenses. These lenses are interpreted as fecal pellets due to their internal structure. Internally they appear as aggregates of clay and silt sized spherical quartz grains, which are possibly microsfossils.

C: Higher power view of the nature of the fecal pellets. Yellow arrows mark some pellets where the internal structure of aggregates of tiny quartz spherical clasts is most obvious.

**Mudstone microfacies description:**
Wavy laminated and pelleted, organic matter-rich, silt-, and clay-bearing mudstone.
A: Low power view (brightness adjusted) show hint of alternating lighter and darker laminations.

B: Low power view of laminated fabric with light coloured (dusty cream to light brown) quartz silt and clay rich lenses. The lower one resembles other lenses described as pellets from IC 4.7, 4.10, and 4.11, and may be a fecal pellet. The upper lense is more irregular in shape and may be a burrow.

C: Medium power view of the area enclosed in red box in B.

D: High power view of area enclosed in red box in C showing the quartz silt and clay fill of the “lense”. The quartz fill has the same texture as that described in the fecal pellets of IC 4.10 and 4.11, being composed of many small spherical quartz grains, possibly microfossils.

**Mudstone microfacies description:**
Wavy laminated and pelleted, clay-rich, silt- and organic matter-bearing mudstone.
**Plate 21: IC 4.13 Thin Section**

A and B: Low power views showing the laminated fabric of this sample, the common quartz silt-rich pellets and the abundant silt grains.

C: Medium power view of slide, with quartz silt-rich pellets highlighted by green arrows.

D: Medium power view of sample, with silt-poor, darker lamination towards the top and a lighter coloured lamination occupying most of the remainder of the slide with observable higher silt content. The yellow arrow points to a possible sponge spicule or echinoderm fragment.

**Mudstone microfacies description:**
Laminated, silt-, clay-, and organic matter-bearing mudstone.
A and B: Low power view shows the wavy to lenticular lamination fabric of this sample. Light coloured laminations have abundant clay and quartz silt lenses, probably pellets. The darker laminations have less silt, and less light-coloured lenses / pellets, but contain more finer-grained clay and organic matter.

C: Medium power view shows alternating light and dark laminations, with lenses in this case being common also in the darker laminations. The area enclosed in the red box is magnified in D.

D: High power view of area in C. Red arrow points to a light dusty brown, almost spherical grain, which may be a phosphate grain or carbonate grain. The green arrows point to light coloured (clear to dusty cream) quartz silty and clay-grade lenses or pellets.

**Mudstone microfacies description:**
Wavy to lenticular laminated, silt-, and organic matter-bearing mudstone.
Appendix 9

Plate 1: NB 15 Mudstone Microfacies

A and B: Low power photomicrograph. Note the disrupted laminations caused by Bioturbation. Green arrow in B is a clay filled burrow.

C: Higher power view, showing round silt clasts (yellow arrow points to an example), that were interpreted to consist of quartz. The red arrow points to an example of a macrofossil shell fragment.

Mudstone microfacies description:

Bioturbated, relic laminated, quartz and/or carbonate cement-, silt-, macrofossil-bearing mudstone.
Plate 2: NB 16 Mudstone Microfacies

A: Low power view shows the thickly laminated fabric of alternating silt-rich and clay- and organic matter-rich laminations.

B: Medium power view illustrating the nature of the silt fraction, towards the top of the photomicrograph there is a very fine silt-rich lamination.

C: High power view, yellow arrow points to a lens that appears to be carbonate cemented (this is also shown in the foreground of B).

Mudstone microfacies description:
Thickly laminated, silt-, organic matter-, and carbonate-cement-bearing mudstone.
Plate 3: NB 26 Mudstone Microfacies

A: Low power view displays the thickly laminated fabric of alternating silt-rich and clay- and organic matter-rich laminations.

B: Medium power view of poorly sorted silt fraction, in a clay- and organic matter-rich lamination. The yellow arrow points to a lens, interpreted to be a fecal pellet. Towards the top of the photomicrograph there are two long thin bands of carbonate cemented lenses.

**Mudstone microfacies description:**
Thickly laminated, silt-, organic matter-, carbonate cement, and pellet-bearing mudstone.
Plate 4: NB 29 Mudstone Microfacies

A: Low power view of the bioturbated fabric of NB 29. The burrows have a dark brown clay fill, and are mostly horizontal with one vertical burrow (lower to middle left).

B: Medium power magnification of vertical burrow in A.

C: Medium power view illustrating a relic lamination fabric.

D: Medium power magnification of an horizontal burrow in A.

**Mudstone microfacies description:**
Bioturbated, relic laminated, clay-rich, organic matter- and silt-bearing mudstone.
Plate 5: NB 17 Mudstone Microfacies

A: Low power view of the laminated fabric of NB 17, consisting of alternating light-coloured carbonate cement rich, and dark-coloured clay and organic matter-rich laminations. The lamination marked with the yellow arrow is rich in fecal pellets.

B: medium power magnification of NB 17, also showing the laminated fabric, and a carbonate cemented lens in the middle (green arrow). Note the abundance of dark organic matter.

**Mudstone microfacies description:**
Laminated, organic matter-rich, pellet-, silt-, and carbonate cement-bearing mudstone.
Plate 6: NB 18 Mudstone Microfacies

A: Low power view of NB 18. The thickly laminated fabric is not very apparent when magnified. The yellow arrow points to a clay or fecal pellet. The slide is rich in organic matter, and silt is abundant (as carbonate grains and as microfossils or macrofossil fragments).

B: High power view of the nature of the silt fraction. The yellow arrow points to an example of a microfossil or macrofossil fragment (e.g. sponge spicule, or radiolaria).

C and D: BSE images of NB 18 show that it is carbonate-rich and clays are not common. This was not obvious from optical examination in transmitted light. (C= carbonate, OM = organic matter, F = fracture).

Mudstone microfacies description:
Thickly laminated, organic matter-rich, carbonate cement-, silt-, microfossil-, and pellet-bearing mudstone.
Plate 7: NB 19 and 20 Mudstone Microfacies

A and B: low and high power views of NB 19. Carbonate cemented burrows are illustrated amongst a clay-rich groundmass in A. The yellow arrow in B points to a crinoid ossicle.

C and D: Low power views of NB 20. The green arrow points to a clay-filled burrow in a carbonate cemented lamination. Carbonate cemented burrows are shown in a dark clay-rich groundmass in D.

Mudstone microfacies description:
Bioturbated, relic laminated, carbonate cement-, clay-, and silt-bearing mudstone.
Plate 8: NB 21 Mudstone Microfacies

A: Low power photomicrograph. This slide was very dark, but without magnification a thickly laminated fabric is observable. Note the dark colour, interpreted to indicate this sample is rich in organic matter.

B: High power view of NB 21, with yellow arrow pointing to a pellet.

C and D: Low and high power BSE images of NB 21. BSE analysis showed that quartz dominated the silt and clay size-fraction. Clay minerals were present but not abundant. Pyrite was abundant. Some high reflectance coefficient equant grains have been interpreted as siderite, but could also be pyrite.

**Mudstone microfacies description:**

Thickly laminated, organic matter-rich, silt-, and pellet-bearing mudstone.
Plate 9: NB 22 and 23 Mudstone microfacies

A: Low power view of NB 22. The wavy laminated fabric of this sample is hard to clearly see in photomicrographs. The laminations consisted of alternating silt-rich and less silty laminations.

B: Higher power view of NB 22. The yellow arrow points to a lens, interpreted to be a fecal pellet that appears to be carbonate cemented.

C: Low power view of NB 23, which was similar in fabric and component parts to NB 22. It also displays a wavy laminated fabric, and contained fossil fragments, pellets, silt and organic matter.

D: The BSE image showed that this sample is rich in carbonate silt and cement (C). Possible areas of vuggy porosity (V) are also highlighted.

**Mudstone microfacies description:**
Wavy laminated, carbonate-rich, organic matter-, pellet-, silt-, and fossil fragment-bearing mudstone.
Plate 10: NB 24, 25, and 27 Mudstone Microfacies

A: NB 24, low power view show distinct change in lamination from a clay-rich lamination to a lamination with abundant silt (yellow dashed line separates the laminations). The yellow arrow points to a microfossil or macrofossil fragment silt clast (e.g. sponge spicule).

B: NB 25, low power view shows the laminated fabric, dominated by thick silt-rich laminations with thinner laminations rich in clay-sized components. The silt grain in the yellow circle is shown in a higher magnification in C.

C: The green arrow (silt grain from B) points to a crinoid ossicle. The red arrow highlights an example of a light-coloured lens, interpreted to be a fecal pellet.

D: NB 27. This slide was very dark and its thickly laminated fabric could only be observed without magnification. Its dark colour has been interpreted to indicate organic richness. The left hand side of the slide contains many holes, probably caused during the production of the thin section.

**Mudstone microfacies description:**
Thickly laminated, organic matter-rich, silt-, pellet-, and microfossil-bearing mudstone.
Plate 11: NB 28 Mudstone Microfacies

A: NB 28 was also a very dark slide but it showed a hint of lamination that appeared to be disrupted, which was interpreted to indicate slight Bioturbation. The yellow arrow points to a crinoid ossicle. The dark nature of the slide was interpreted to indicate organic richness.

B: The green arrow points to a microfossil silt rich lamination (possible coccolithophores or sponge spicules).

Mudstone microfacies description:
Laminated, slightly bioturbated, organic matter-rich, silt-, and microfossil-bearing mudstone.