



Roinn Cumarsáide, Gníomhaíthe
ar son na hAeráide & Comhshaoil
Department of Communications,
Climate Action & Environment



Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

**Research Programme
- Short Calls, Final Report -**

For official use only

Date received:

Ref. No.:

Final report:

Lead Applicant Name	Deirdre Lewis
Email	dlewis@slrconsulting.com
Host Organisation name	SLR Environmental Consulting (Ireland) Ltd
Project Title	Investigation of Irish Carboniferous Palaeokarst for CO ₂ Geological Storage & deep geothermal resource
Contract Number	2017-sc-003

Date:

14/11/2018

This report covers the period November 1st 2017 to October 31st 2018



2. (a) Project information:

Final project report (max 2500 words, excluding figures and headings):

- (i) Progress of objectives and scientific/engineering targets beyond the state of the art & methods used

This project set out to compile, map, quantify and assess evidence of presumed ancient karst features in Ireland based on quarries, deep mines, borehole records, seismic data, and known uplifted structural blocks. The final deliverables are additional GIS layers to the existing SEAI Geothermal Play Fairway Analysis Project which is a guide to deep drilling targets for enhanced porosity and permeability at depth onshore Ireland. It is a further development of the Play fairway Analysis Methodology and Toolkit for deep exploration onshore Ireland leading to a demonstration deep drilling project.

The study commenced with a literature review of the Irish Carboniferous and international references to palaeokarst as a potential reservoir for hydrocarbons, geological storage of carbon dioxide and geothermal energy. Several exploration techniques to locate palaeokarst were identified in the literature and techniques suitable for onshore Ireland were selected.

This was followed by a compilation of evidence of deep karstification and dolomite formation onshore Ireland from published literature and publically available industry reports. A number of focus group interviews were held with senior geologists, Deirdre Lewis, Paul Gordon, John Kelly and Gareth LI. Jones, who have a long history of mineral exploration, drilling and quarry mapping in the Irish Carboniferous. These facilitated focus group interviews helped the researchers to develop the exploration model for deep karst within the Irish Carboniferous.

The compiled evidence of deep karstification and dolomite formation onshore Ireland was georeferenced where possible and entered into a GIS database. The anecdotal evidence of "dropped rods" and deep karstification observed in cores and quarry outcrop was verified and assigned to specific locations within the GIS project. Data include papers, maps, drillhole records and geological anecdotal evidence.

Based on the literature review of the Irish Carboniferous and discussions with mineral exploration geologists John Kelly, Deirdre Lewis, Paul Gordon and Gareth LI. Jones potentially karstified target horizons within the Irish Carboniferous were identified. The basins where these potentially karstified target horizons are buried at sufficient depth where then identified. Using SLR in-house databases, information from ICRAAG researchers, industry professionals and government open file drill hole data a GIS project database for the target area was generated. An application was made to industry to provide access under a non-disclosure agreement to key seismic lines.

An appropriate analogue for deep karst reservoir development from the oil industry was identified (Loucks, 2003). Parameters indicative of deep karst development in core, wireline logs and seismic were identified (Fritz, et al., 1993). These parameters were then applied to well and seismic data supplied by the mineral exploration industry in the target basin, taking current Irish Deep Palaeozoic geological interpretations beyond the state of the art.

Based on new seismic interpretation integrated with borehole data a target drilling location was identified.



and overlain with the GSI bedrock and outcrop maps to confirm the presence of karst features at the surface and at depth.

4. Seismic Interpretation – “Drilling Location”

The project used a common Oil & Gas exploration technique - Seismic Analysis, to identify deep karst features. The results of the seismic analysis, accompanied by evidence in the literature and anecdotal evidence from experts led us to infer the presence of a ‘Coalesced Collapsed Palaeocave’ in the Kilmurry region with substantial confidence.

5. Skills transfer

Two new staff members Charlie Carlisle MSc and Lloyd Vaz MSc. Received “training-through-doing” on a range of new skills such as understanding of deep carbonate geology, structural framework of the Irish carbonate basins, data acquisition, GIS data analysis, seismic interpretation, well log analysis etc

6. Drilling opportunity

An opportunity exists to collaborate with the mineral exploration sector to drill a deep exploratory research borehole to test the ‘coalesced collapsed palaeocave’ exploration model.

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Compile data	Month 3	Completed
2	Integrate data into GIS	Month 5	Completed
3	Mid Term Review	Month 6 April 16th	Completed
4	Map high graded deep palaeokarst potential	Month 8	Completed
5	Source seismic data over high graded area	Month 9	Completed
6	Interpret seismic for palaeokarst	Month 10	Completed
7	Seismic Criteria for Identification of Deep Palaeokarst	Month 11	Completed
8	Identify drillhole location	Month 12	Completed

Publications to date: *Please use format below and provide a copy of the presentation*

[Conference Publication] Vaz, L.; Lewis, D.; O'Neill, N; Blake, S.; (2018) Investigation of Geothermal Potential in the Irish Carboniferous Palaeokarst *Geoscience 2018*, Dublin, Ireland, 06-NOV-18



- (ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

The background to the geological storage of CO₂ and deep geothermal energy and their importance to Ireland's energy strategy was compiled and discussed. The interviews with veteran geologists were completed and the evidence compiled was transferred to a GIS database for further interrogation.

Following interrogation of the GIS database (including 2D seismic coverage onshore Ireland) two basins were identified as having the potential to contain deep karst reservoirs in the Waulsortian Mudbank facies. The Shannon Trough contains Waulsortian mudbank facies at depths exceeding 800m, a criterion that meets the requirement for CO₂ geological storage and deep geothermal heat potential. A successful application was made to Hannan Metals to obtain access to seismic data that over the Shannon Trough. Additional borehole data adjacent to the seismic lines was accessed, integrated with the seismic data and interpreted. Drilling targets were identified.

There was some unexpected delay of a few days when access to seismic and well data held by iCRAG was denied. SLR negotiated a separate NDA with Hannan Metals to allow SLR team members Sarah Blake and Lloyd Vaz access to the data.

- (iii) Outputs (please provide a short description and complete the table below)

1. Literature Review - "Regional understanding of Geothermal Resources and CCS"

A literature review was carried out to update information from previous studies by SLR staff, especially regarding the operational status of previously described CCS and geothermal projects. References included in the Final Report (attached)

2. Consultations – "Regions of interest"

Gareth Ll. Jones was consulted in order to capture his deep knowledge of karstic expression across Ireland. Further interviews were held with karst expert Dr. John Kelly in late March/early April. Contact with John Colthurst, professional geologist, has identified locations of deep karst intersection near Littleton, Co. Tipperary (PL3321), characterised by caverns and drilling problems (such as loss of drill rods). Further consultations were help with experts Brian McConnell and Monica Lee in the Geological Survey, and Chris Bean in DIAS, as well as with SLR project leaders and project associates. In addition, consultation with John Kelly suggested a particular area of interest around PL 3695 Piltown. The Cretaceous Ulster White Limestone is also well exposed and can be used in this project for analogue comparisons (Simms, 2000; Kelly, et al, 1996).

3. Data compilation in GIS – "Project GIS Database"

Data acquired through the consultations was compiled in a GIS Project (available to be transferred via SLR FTP Site). By integrating publicly available datasets with in-house exploration and geothermal borehole databases, an overview of deep geological data has emerged. By incorporating data compiled as part of the SEAI Play Fairway Analysis, the SLR Team have access to a number of wells not previously identified on public databases and their temperatures, depths and water levels. Maps of karst identified in Drew and Jones' 2010 paper were digitized



4. Data/outputs submitted with final report *(please list the documents, presentations, datasets etc. submitted with this report)*

- a. **"Investigation of Irish Carboniferous Palaeokarst for CO₂ Geological Storage & deep geothermal resource"** (Prepared for: The Geological Survey Client Ref: 2017-SC-003)
- b. **GIS Project (501.0026.00006_Final GIS Project_131118)** available for download from SLR FTP site.
- c. **Geoscience 2018 Poster: "Investigation of Geothermal Potential in the Irish Carboniferous Palaeokarst"**

SUPPLEMENTARY MATERIAL

(This section will be included in your published report unless otherwise instructed. If you have a published report, publication, etc. you may include it here).



Rialtas na hÉireann
Government of Ireland



Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann



INVESTIGATION OF IRISH CARBONIFEROUS PALAEOKARST FOR CO₂ GEOLOGICAL STORAGE & DEEP GEOTHERMAL RESOURCE

Prepared for: The Geological Survey of Ireland
GSI Ref: 2017-SC-003

SLR Ref: 501.0026.00006
Version No: V0
October 2018



AUTHORS

L. VAZ, DR. D. LEWIS, N. O'NEILL, DR. S. BLAKE

BASIS OF REPORT

This document has been prepared by SLR Environmental Consulting (Ireland) Limited (SLR) with reasonable skill, care and diligence, and taking account of the manpower, timescales and resources devoted to it by agreement with Geological Survey of Ireland (GSI) as part or all of the services it has been appointed by GSI to carry out. It is subject to the terms and conditions of that appointment.

SLR shall not be liable for the use of or reliance on any information, advice, recommendations and opinions in this document for any purpose by any person other than the GSI. Reliance may be granted to a third party only in the event that SLR and the third party have executed a reliance agreement or collateral warranty.

Information reported herein may be based on the interpretation of public domain data collected by SLR, and/or information supplied by the GSI and/or its other advisors and associates. These data have been accepted in good faith as being accurate and valid.

The copyright and intellectual property in all drawings, reports, specifications, bills of quantities, calculations and other information set out in this report remain vested in SLR unless the terms of appointment state otherwise.

This document may contain information of a specialised and/or highly technical nature and the GSI is advised to seek clarification on any elements which may be unclear to it.

Information, advice, recommendations and opinions in this document should only be relied upon in the context of the whole document and any documents referenced explicitly herein and should then only be used within the context of the appointment.

CONTENTS

1.0	INTRODUCTION AND RESEARCH PURPOSE	1
2.0	BACKGROUND.....	2
2.1	Karsts.....	2
2.2	Limestones in Ireland	2
2.3	Karst Systems in Ireland	5
2.4	Regional Dolomitization of Waulsortian in Ireland	6
2.5	CO ₂ Storage and Geological Requirements	7
2.5	Geothermal and Geological Requirements	8
3.0	METHOD OF INVESTIGATION	9
4.0	RESULTS/FINDINGS.....	10
4.1	Investigation Strategy	10
4.2	Exploration Model.....	10
4.3	Evidence of Karstification.....	11
4.4	GIS Database	12
4.5	Seismic Analysis	12
5.0	DRILLING PROPOSAL.....	19
6.0	RECOMMENDATIONS	20
7.0	CONCLUSIONS	21
8.0	BIBLIOGRAPHY	22

DOCUMENT REFERENCES

FIGURES

Figure 1. Outlines of the Carboniferous Basins overlaid on the GSI 500K Bedrock Geology Map	2
Figure 2. Thickness of Waulsortian facies in Ireland during late Tournaisian times. (Lees & Miller, 1995).....	4
Figure 3. A & B. Distribution and spatial variation of Waulsortian bank facies in Ireland. (Murray & Henry, 2018).....	4
Figure 4. A & B. Generalised map & cross section showing regional dolomitization (Hitzman et al, 1998).....	6
Figure 5. Burial evolution of a palaeocave system (Loucks, 1999)	10
Figure 6. (left) Illustration of the Ouachita thrusting and its influence on fluid flow in the Ellenburger formation, W. Texas (Loucks, 1999). (right) Hercinian orogeny and its hypothesised influence on the dolomitization of the Waulsortian in the Irish Midlands (Hitzman, et al., 1998).	12
Figure 7. Compilation of data into a single GIS Database.....	13
Figure 8. 3-D Seismic example over an Ellenburger palaeocave system, West Texas (Loucks, 1999)	14
Figure 9. Seismic dip section of Ordovician Palaeokarst strata, Central Tabei uplift, Tarim Basin, Western China (Zeng , et al., 2011)	14
Figure 10. Kilbricken Dataset – boreholes and seismic lines. (<i>Data Courtesy of Hannan Metals</i>) ...	15
Figure 11. Kilbricken Dataset – example of 2012 2D seismic line (<i>Data Courtesy of Hannan Metals</i>)	16
Figure 12. Kilbricken Dataset – example of 2017 2D seismic line (<i>Data Courtesy of Hannan Metals</i>)	17
Figure 13. Focused seismic section of a 2017 2D line with projections of cavity/brecciation locations and project interpretations of sag features and faults (<i>Data Courtesy of Hannan Metals</i>).....	18
Figure 14. Proposed location for borehole to drill Kilmurry Prospect - Coalesced Collapsed Palaeocave with target at ~900m depth. Comparison with Ellenburger conceptual model. (<i>Data Courtesy of Hannan Metals</i>).....	19

TABLES

Table 1. Summary stratigraphic column for the Shannon Trough (Strogen, 1988) (Somerville & Jones, 1985), (Somerville, et al., 1992)	3
Table 2. Post Carboniferous episodes of erosion & karstification (Drew & Jones 2000)	5
Table 3. Geological Criteria for CO ₂ Storage	8

APPENDICES

Appendix 01: Key Boreholes

1.0 Introduction and Research Purpose

The National Mitigation Plan July 2017 (NMP) states that subject to commercial and technical considerations, Carbon Capture and Storage (CCS) could facilitate decarbonisation of Ireland's electricity sector and recommends an action to explore the feasibility of utilising suitable reservoirs for CO₂ storage. The NMP also recommends continuing the assessment of Ireland's geothermal energy potential by targeting deep geological settings including deeply karstified limestone and fracture zones, requiring exploration by onshore seismic surveys and borehole drilling.

Karstified reservoirs within Tournaisian and Visean carbonates of the Campine Basin in Belgium comply with the depth and safety restrictions for geological storage of CO₂ (Laenen, et al., 2004; DEWAIDE, et al., 2014). The hottest spring waters in Britain emanate from palaeokarst in the Carboniferous Limestone near Bath (Adams et al 2017). There is abundant evidence from quarries, outcrops and boreholes of Palaeozoic palaeokarst in Ireland (pers comm Jones & Kelly 2017). The purpose of this seed project, funded by the Geological Survey Ireland (GSI), is to identify targets for deep borehole drilling to assess geothermal energy resources and CO₂ storage potential. The project will also address some of the GSI Research Road Map's Challenges¹.

Almost half of the island of Ireland is underlain by limestone of which a high proportion has been karstified. In addition to the evidence for uplift and karstification in the Tertiary, there are indications that uplift and karstification occurred in the Jurassic and Permian in Ireland (Drew & Jones, 2000). Anecdotal drilling evidence (e.g. "drops of rods" & "non recovery features") from mineral exploration drilling in Ireland can be confirmed and mapped from borehole records. There is now a significant seismic data set for onshore Ireland that can be examined for evidence of deep karstification, or presence of dolomite, at depth using oil and gas seismic interpretation techniques developed from known West Texas Palaeozoic karst oil reservoirs.

The project objectives are to:

1. Compile, map, quantify and assess evidence of presumed ancient karst features in Ireland
2. Add additional GIS layers to the existing SEAI Geothermal Play Fairway Analysis Project
3. Identify a target location for a borehole to assess deep geothermal and CO₂ storage potential onshore Ireland

SLR has a long track record of managing drilling operations for mineral exploration programmes onshore Ireland and working with the Sustainable Energy Authority of Ireland (SEAI), IRETherm and iCRAG to evaluate Ireland's deep geothermal potential and CO₂ geological storage potential. SLR also brings international experience in hydrocarbon exploration techniques.

The authors acknowledge the significant input to this project from Michael Hudson of Hannan Metals Ltd. who kindly provided access to seismic and borehole data; Murray Hitzman, John Walsh, Jennifer Craig, John Conneally, and Koen Torremans of iCRAG who assisted the work; Gareth Ll. Jones and Paul Gordon who provided extensive references and anecdotal evidence of deep karst not recorded in drilling reports.

¹ GSI Research Roadmap

Challenge 1: Sustainability & Management of Earth Resources under water resources and geoenergy. It also addresses Challenge 2: Geological Hazards and Climate in that CO₂ storage from gas fired electricity generation contributes to national emissions reduction targets.

2.0 Background

2.1 Karsts

According to the Oxford Dictionary of Earth Sciences, 2008, Karst is defined as any region underlain by limestone and characterized by a set of land-forms resulting largely from the action of carbonation, a chemical weathering process involving a reaction between dilute carbonic acid, derived from the solution in water of free atmospheric and soil-air carbon dioxide, and a mineral.



Karst systems may be formed as epigenic (unconfined) karst or hypogenic (confined) karst, with the primary difference being the principal vectors of fluid movement (descending vs ascending) and recharge sources (recharge from overlying or adjacent unit vs recharge from depth) to the given unit (Zhu, et al., 2017). Epigenic karst systems have been widely studied and well described in the literature. Hypogenic karst systems are formed by fluids that recharge the soluble formation from deeper levels, driven by appropriate energy sources (like hydrostatic pressure). The acidic hydrothermal fluids dissolve the carbonates and may form associated minerals, thus producing a series of detectable changes that are reflected in the geochemistry and mineralogy.

The goal of this study is to evaluate the potential of karst onshore Ireland to store CO₂ and/or to act as a hydrothermal reservoir for geothermal heat. Therefore, the study only addresses deep-seated karsts i.e. epigenic paleokarst², hypogenic karsts or a combination of the two. A few concepts and tools have been developed to help identify and locate paleokarst reservoirs in the subsurface including wireline logs,

cores, bit drops and 2D and 3D seismic data (1999). Geophysical logs can be used to identify permeable fractured zones in karstified

Figure 1. Outlines of the Carboniferous Basins overlaid on the GSI 500K Bedrock Geology Map

(Loucks, 1999) to identify massive

carbonates (Laskow, 2011). Karst related paleocave systems in the Lower Ordovician Ellenburger Group in Central Texas are important petroleum reservoirs onshore USA (Loucks, 1999). The concepts and tools described in the literature will be applied to Irish onshore exploration for paleo- and deep karst.

2.2 Limestones in Ireland

Limestones underlay almost half of Ireland, with significant carbonate deposition occurring in the Lower Carboniferous. Two important basins from the viewpoint of this study are the Dinantian Age - Dublin Basin and Shannon Trough (Figure 1) that host early Dinantian deep-ramp limestones (and shales) and late Dinantian platform and basin limestones (Strogen, et al., 1996). The Lower Carboniferous thickness in both basins is ca. 2-

² Carbonates exposed at the surface may form epigenic karsts. When these karst features are buried or consumed by a marine transgression and overlain by sediments or further carbonate creation, they form subsurface paleokarst.

3km and subsidence rates appear to be comparable, despite the differences in sediment fill. Both Basins have undergone a low degree of tectonic inversion, with gentle folding and minor overthrusting.

Age	"General" Term	Northwest Limerick - Shannon Trough	Approx. Thickness
Early Arundian to Early Asbian	Supra-"Reef"	Mungret Formation	190 – 500m
		Cooperhill Formation	
Late Chadian to Early Arundian		Carrigogunnel Volcanic Formation	250 – 550m
Chadian		Lough Gur Formation	50 – 100m
Late Courceyan to Early Chadian	"Reef"	Limerick Limestone Formation (Waulsortian Mudbank Limestones)	140 – 440m
Mid to late Courceyan	Argillaceous Bioclastic Limestone (ABL)	Ballysteen Limestone Formation	190m
		Ballymartin Limestone Formation	45m
	Lower Limestone Shales	Ballyvergin Shale Formation	6m
Early Courceyan	Upper Old Red Sandstone	Ringmoylan Shale Formation	30m
		Mellon House Formation	40m
		Old Red Sandstone "facies"	Base not seen
Late Devonian			

Table 1. Summary stratigraphic column for the Shannon Trough (Strogen, 1988) (Somerville & Jones, 1985), (Somerville, et al., 1992)

Within the deep-ramp limestones, two key units were identified that would be the focus of this project. The early Courceyan unit, referred to as the Ballysteen formation, is made up of a sequence of calcareous shales, argillaceous limestones and limestones. The late Courceyan unit comprises of the 'Waulsortian banks' that is represented by a series of accreted carbonate build-ups (Murray & Henry, 2018). This unit is referred to as the Feltrim Formation in the Dublin Basin and the Limerick Formation in the Shannon Trough Basin (Strogen, et al., 1996). The Waulsortian banks ('mud-mounds) occur in tabular, knoll and sheet forms (Lees & Miller, 1995). The thickness of bank aggregates may be up to 1 km and individual banks may range from less than a metre to several metres. The thickest bank aggregates are observed to be around the south eastern zone of the Shannon Trough Basin (Murray & Henry, 2018) (illustrated in the Waulsortian Facies isopach map from (Lees & Miller, 1995))

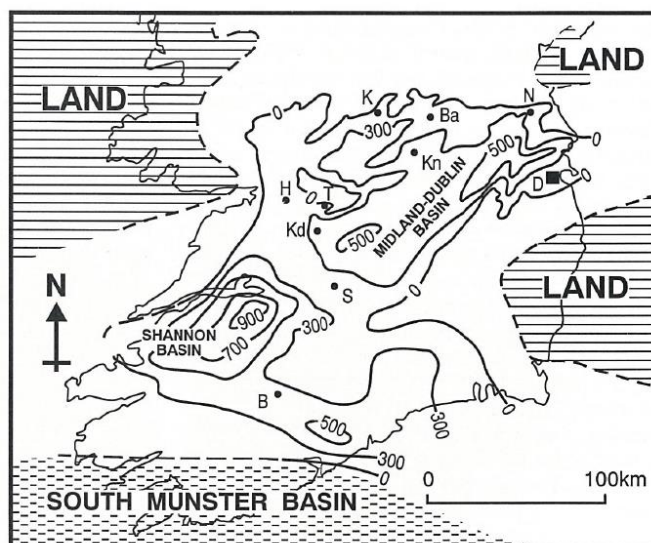


Figure 2. Thickness of Waulsortian facies in Ireland during late Tournaisian times. (Lees & Miller, 1995)

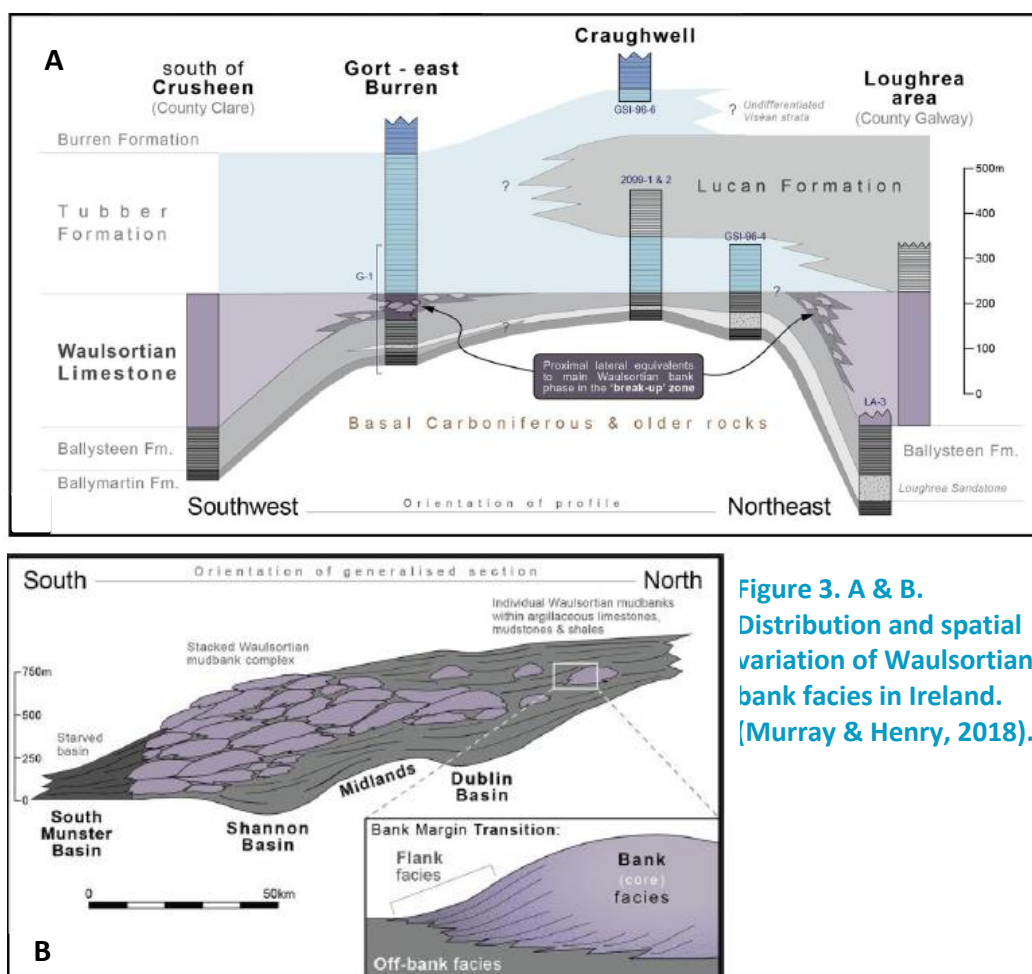


Figure 3. A & B. Distribution and spatial variation of Waulsortian bank facies in Ireland. (Murray & Henry, 2018).

2.3 Karst Systems in Ireland

Drew & Jones, 2000, discusses compiled data from published and unpublished sources and evaluates Pre-Quaternary Ancient Karst features in Ireland that were recorded in relation to Carboniferous and Cretaceous limestone outcrops. They locate and describe ancient karst features, isolated limestone hills, sediment-infilled channels/caves, and infilled enclosed depressions. Sediment infilled channels have been reported of depths <100 m and few kilometres in length. Almost all these features are Mesozoic or younger. Available literature on these features suggests that significant karstification may have occurred in mid to late Tertiary times but only a minority of features can be assigned a minimum date with any confidence. It is difficult to assess the timing of erosion that may have caused karstification of the Carboniferous limestones, but several episodes are postulated (Table). The research of Drew and Jones confirms periods of erosion that have caused epigenic karstification in the past and could potentially have caused preservation of paleo-karsts within the Irish Carboniferous limestones. There remains the additional potential for hypogenic karstification formed by fluids that recharge the soluble formation from deeper levels, driven by appropriate energy sources (like hydrostatic pressure).

ERA	PERIOD	EPOCH	SOUTH-EAST (after Keeley 1996)	AGE OF DEPOSIT * = marine	MIDLANDS (after Naylor 1992)	ULSTER BASIN
CENOZOIC	Quaternary	Holocene	karstification	west Burren caves	karstification	karstification
		Pleistocene	cold climate	cave bones dated >45ka cave calcite dated >350ka	cold climate	cold climate
	Tertiary	Pliocene	erosion >0.5km uplift	Galmoy, Pollnahalia	erosion	L. Neagh clays & lignites igneous activity & interbasaltic soils erosion / karstification
		Miocene		Cormackstown, Hollymount, Lisheen, Tynagh	/ karstification	
		Oligocene		Aughinish Loughshinny Ballygiblin Ballymacadam	/ mantling	
		Eocene				
		Palaeocene	erosion >1km uplift	Garron Point	erosion / karstification	
	Mesozoic	Upper Cretaceous	sedimentation >0.5km	Ballydeenlea *	sedimentation variable around islands/ in valleys?	sedimentation <3km
		Lower Cretaceous	sedimentation <0.5km	Piltown (*)	erosion	
		Jurassic	erosion/ karstification >1.5km uplift	Cloyne	erosion	sedimentation >0.25km
		Triassic	sedimentation >1km		Topography Established	
PALAEOZOIC Upper parts	Permian	Upper			erosion	sedimentation <3km
		Lower	erosion >2km uplift			
	Carboniferous	Silesian	sedimentation ~2km		sedimentation	
		Dinantian	erosion will include the karstification of limestones			

Table 2. Post Carboniferous episodes of erosion & karstification (Drew & Jones 2000)

Of the two key limestone formations discussed in the previous section, the massive Waulsortian Limestone (Feltrim/Limerick Formation) is considered to be more susceptible to karstification processes as compared to the impure Ballysteen Formation. The Waulsortian is known to be susceptible to dolomitization in zones controlled by faulting (Murray & Henry, 2018). Evidence of regional dolomitization, followed by hydrothermal mineralisation has been observed at Lisheen, in County Tipperary. Deeper fault structures have proven to be conduits of fluid flow from deep sources and karst features have been observed at depths >200m. Core from the Waulsortian Limestones from the Dublin basin showed evidence of dissolution features at depths of 250m-300m and possibly up to 500m (Blake, et al., 2016b). This indicates that the Waulsortian Limestone may host karst features, most probably of the hypogenic category.

2.4 Regional Dolomitization of Waulsortian in Ireland

Research analysing the extent and character of dolomitization within the Waulsortian in Ireland has been carried out in relation to ore deposits. The Waulsortian limestone has been dolomitized throughout much of south-eastern Ireland (Hitzman, et al., 1998). The dolomitization is believed to be associated with the Hercynian Front – with a dolomitized zone (~100km wide) immediately north of the Hercynian Front and almost no dolomitization to the south. The dolostone is made up of 2 components – *replacive dolomite* (*planar or non-planar*) and *infilling dolomite*. The average grain size of the replacive dolomite and the abundance of infilling dolomite decrease progressively towards the northern part of the proposed Dolomitized zone.

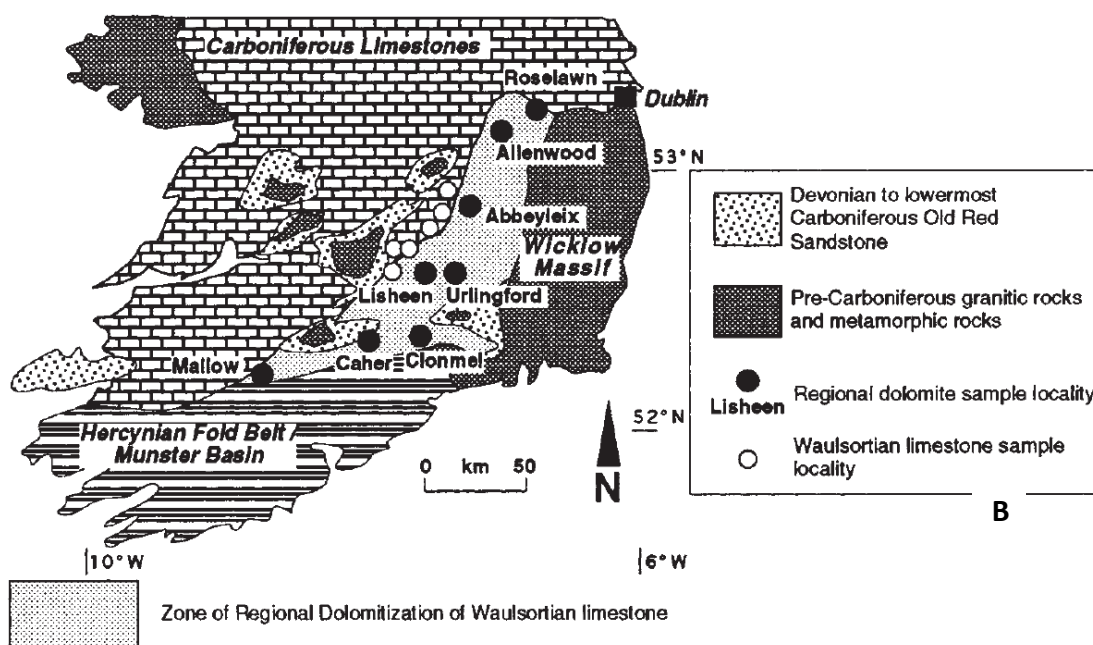
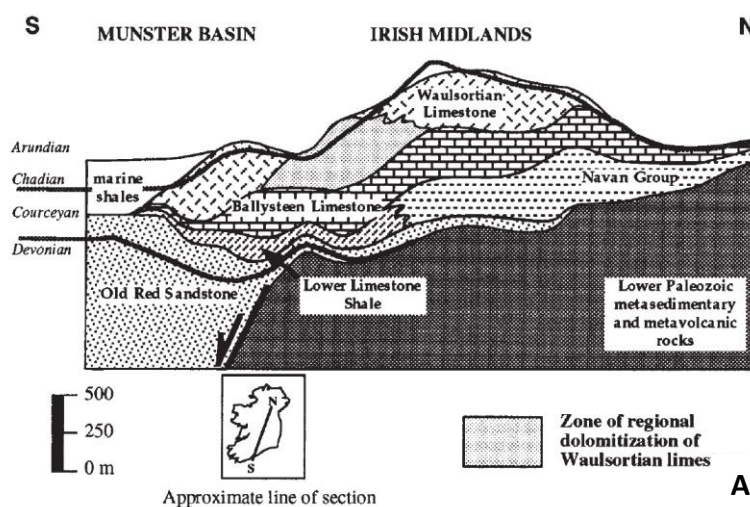


Figure 4. A & B. Generalised map & cross section showing regional dolomitization (Hitzman et al, 1998)

The regional replacive dolomitization is argued to have occurred at a time when the Waulsortian limestone was at a shallow depth, by a cover of 0.5 to 2.5 km of sediments and sea water. Taking into consideration the depth of burial at the time of dolomitization, fluid inclusion studies described in (Hitzman, et al., 1998) show that *infilling dolomite* could possibly be a result hydrothermal fluid migration from deeper sources, with fluids flowing northwards from the South Munster Basin. Even though early diagenesis may have occluded the high initial porosity and permeability of the Waulsortian mudbanks, evidence of regional infilling dolomitization suggests that significant permeability was maintained to allow fluid flow. Chadian age normal faults found within the area of regional dolomitization may or may not have had any control on the early replacive dolomitization. However, their significant presence around areas of abundant *infilling dolomite* occurrences may suggest a Chadian structural control. Later work (Gregg, et al., 2001), stated no systematic regional variation in replacive or infilling dolomite. The alternate hypothesis proposed was that early diagenetic

dolomite may have undergone later diagenesis, resulting in late void-filling precipitation. Both hypotheses can be supported by the available data. However, they provide evidence of the complex history involved in regional scale dolomitization of the Waulsortian in Ireland.

With respect to karstification, (planar) replacive dolomite, which is a result of early diagenesis, may be explained to have originated due to the action of sea water and meteoric water, either during a mixing event or in subsequent phases. Conditions that would allow such an event would be during periods when the Waulsortian mounds were sub-aerially exposed towards the end of their deposition. This would cause one to speculate the existence of karst surfaces at the top of such mounds, as speculatively reported (Hitzman, 1995). An alternative explanation attributes the nature of the planar replacive dolomite to the interaction with ubiquitous hydrothermal fluid – which may indicate potential for hydrothermal geothermal energy.

2.5 CO₂ Storage and Geological Requirements

The concentration of atmospheric carbon-dioxide (CO₂) has been increasing at an alarming rate in recent times. Thus, efforts are being made to investigate the potential of storing captured atmospheric CO₂ in deep-seated geological formation in Ireland. Since the focus of this study is storage potential in deep-seated karstic limestones, in this section we will only discuss the relevant geological characteristics to be considered (CSA Group, 2008) and (Chalaturnyk, 2012).

Geological Characteristic	Comment
Reservoir/Seal Pair	Reservoir: Karstified limestones with primary and secondary porosity to allow infill of gas into pore spaces. Seal: Prevention of upward and lateral migration of infilled gas by an overlying impermeable formation. Integrity of top, bottom and lateral seals to contain the CO ₂ over long periods of time
Structure	Anticlinal folds, sealing faults, isolated limestone mounds
Potential for Hydrocarbons	Non-existent or depleted
Depth	Deeper than ~650m to ensure that CO ₂ is maintained in supercritical fluid phase
Size of Structure / Basin	Volumes available for significant and economical storage
Porosity / Permeability	High porosity as well as high permeability would imply great storage capacity. Presence of micro-fractures, joints, faults, karstification etc could imply greater permeability
Compartmentalisation	Is the reservoir segmented due to faulting? Would it require multiple injection wells?
Pressure / Temperature of reservoir	Solubility, density and buoyancy of CO ₂ will be influenced by PT conditions of reservoir.
Geothermal Gradient	Relatively warmer basins have different criteria from cooler basins
Tectonic Setting	Ireland is known to be weakly seismically active and hence seismicity is not a major concern
Potential for CO₂ reaction with rock	CO ₂ reacts with wall rock in the host reservoir albeit in a generally predictable fashion. However, at depth, natural secondary mineral precipitation will occur and may cause occlusion of the reservoir porosity,

	particularly close to the injection site. (CSA Group, 2008)
Reservoir Recharge: Depletion Drive or Water Drive	Post production, is the natural recharge of available pore space in a reservoir by water or low pressure natural gas? If with water; the reservoir is said to have 'water drive'; if by gas, the reservoir is said to have 'depletion drive'. The latter is more favourable for CO ₂ injection, as the pore space can be refilled to natural levels without over-pressuring, thus reducing the risk of leakage. (CSA Group, 2008)

Table 3. Geological Criteria for CO₂ Storage

The Dublin Basin and the Shannon Trough have been identified as having the potential to contain reservoir generated by deep karstification. The karstified reservoirs within Tournaisian and Visean carbonates of the Carboniferous limestone group in the Campine Basin and the Roar Valley Graben in northern Belgium we considered to comply with the depth and safety restrictions for geological CO₂ storage given their depth below 800m with natural traps and adequate sealing. Therefore, deep karst reservoirs at depths in excess of 800m in the Shannon Trough should not be ruled out as potential targets for geo-sequestration of CO₂ provided adequate sealing can be proven.

2.5 Geothermal and Geological Requirements

Deep geothermal resources are usually referred to as those occurring below 300m (depending on the jurisdiction). Practically most international development occurs from 1000m to a maximum of 6000m with temperatures varying from 50°C to 150°C and higher depending on location and local geology. Deep Geothermal resources are commonly subdivided into Hydrothermal and Engineered Geothermal Systems (EGS), the latter were formally known as Enhanced Geothermal Systems or Hot Dry Rock (HDR). In Ireland low enthalpy hydrothermal resources are the target. Hydrothermal resources in Europe are located in deep aquifers with enhanced temperatures where heat can be easily extracted due to the presence of water as a heat transfer medium.

Several key requirements are necessary for a geothermal play. These are 1) a **source** of heat, 2) a suitably permeable rock mass which can act as a **reservoir** of groundwater which will be the local heat transfer medium and 3) a cover of poorly conductive rock (insulator) which effectively 'blankets' the heat resource and maintains a higher than normal reservoir temperature. Deep zones of structural weakness in the earth's crust can act as pathways for hot hydrothermal fluids to reach shallower depths. Deeply penetrating faults with associated fracture permeability can act as migration pathways for the deep heat **source** to move as hot hydrothermal fluid to shallower reservoir rocks where the heat is stored. The **reservoir** is the porous, permeable, water bearing rock mass that stores the heat from the source. It can be porous and permeable fractured granite, sandstone or carbonate. The reservoir is the geological unit targeted to access the geothermal resource. The insulator is a rock blanket that traps the heat in the reservoir. The insulator strata are very low permeability rocks with low thermal conductivity, such as shales and mudstones.

Any deep reservoirs identified by this study onshore Ireland that result from karstification will be assessed for their suitability as a reservoir for a hydrothermal geothermal resource against the key requirements for a geothermal play outline above.

3.0 Method of Investigation

This project set out to compile, map, quantify and assess evidence of presumed ancient karst features in Ireland based on quarries, deep mines, borehole records, seismic data, and known uplifted structural blocks. The final deliverables are additional GIS layers to the existing SEAI Geothermal Play Fairway Analysis Project which is a guide to deep drilling targets for enhanced porosity and permeability at depth onshore Ireland. It is a further development of the Play fairway Analysis Methodology and Toolkit for deep exploration onshore Ireland leading to a demonstration deep drilling project.

The study commenced with a literature review of the Irish Carboniferous and international references to palaeokarst as a potential reservoir for hydrocarbons, geological storage of carbon dioxide and geothermal energy. Several exploration techniques to locate palaeokarst were identified in the literature and techniques suitable for onshore Ireland were selected.

This was followed by a compilation of evidence of deep karstification and dolomite formation onshore Ireland from published literature and publically available industry reports. A number of focus group interviews were held with senior geologists, Deirdre Lewis, Paul Gordon, John Kelly and Gareth Ll. Jones, who have a long history of mineral exploration, drilling and quarry mapping in the Irish Carboniferous. These facilitated focus group interviews helped the researchers to develop the exploration model for deep karst within the Irish Carboniferous.

The compiled evidence of deep karstification and dolomite formation onshore Ireland was georeferenced where possible and entered into a GIS database. The anecdotal evidence of “dropped rods” and deep karstification observed in cores and quarry outcrop was verified and assigned to specific locations within the GIS project. Data include papers, maps, drillhole records and geological anecdotal evidence.

Based on the literature review of the Irish Carboniferous and discussions with mineral exploration geologists John Kelly, Deirdre Lewis, Paul Gordon and Gareth Ll. Jones potentially karstified target horizons within the Irish Carboniferous were identified. The basins where these potentially karstified target horizons are buried at sufficient depth were then identified. Using SLR in-house databases, information from iCrag researchers, industry professionals and government open file drill hole data a GIS project database for the target area was generated. An application was made to industry to provide access under a non-disclosure agreement to key seismic lines.

An appropriate analogue for deep karst reservoir development from the oil industry was identified (Loucks, 2003). Parameters indicative of deep karst development in core, wireline logs and seismic were identified (Fritz, et al., 1993). These parameters were then applied to well and seismic data supplied by industry in the target basin.

Based on seismic interpretation integrated with borehole data a target drilling location was identified.

4.0 Results/Findings

4.1 Investigation Strategy

The investigation strategy was to identify from the literature and anecdotal evidence where karst features might occur at depths more than 800m (criteria for CO₂ storage and a minimum depth for finding warm hydrothermal fluids). The database includes borehole data and recently acquired seismic data. Because hydrocarbon reservoirs are proven in karst features in the USA techniques and lessons learned from the oil and gas exploration industry were applied to the Irish data.

4.2 Exploration Model

The exploration model for Palaeozoic karst at depth onshore Ireland is based on the coalesced, collapsed palaeocave model developed for the Lower Ordovician Ellenburger Group of the Permian Basin in Texas, USA, which is a prolific oil producer in a ramp carbonate play (Loucks, 1999), see Figure 6.

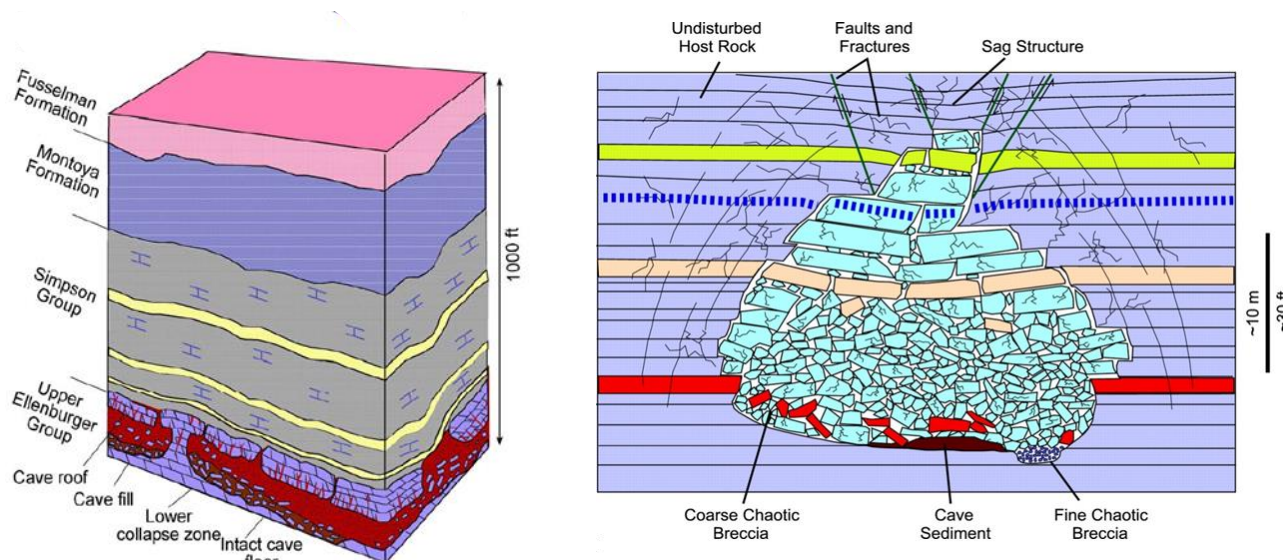


Figure 5. Burial evolution of a palaeocave system (Loucks, 1999)

The Ellenburger Formation is a shallow water carbonate that has been extensively karstified at the Sauk unconformity at the end of the Early Ordovician. Several authors have demonstrated that the karst affected strata at least 300 to 1,000 ft beneath the unconformity (Loucks, 1999). With the occurrence of Ouachita thrusting from the Mississippian through the Pennsylvanian, vast quantities of hydrothermal fluids moved through available permeable pathways within the Ellenburger, producing late-stage diagenesis. Loucks (1999) showed that paleocave systems are products of near-surface cave development, including dissolutional excavation of passages, breakdown of passages, and sedimentation in cave passages. These are followed by later-burial cave collapse, compaction, and coalescence.

As the multiple-episode cave system subsides into the deeper subsurface, wall and ceiling rock adjoining open passages collapses and forms breccias that radiate from the passage and may intersect with fractures from other collapsed passages and older breccias within the system. This process forms coalesced, collapsed-paleocave systems and associated reservoirs that are hundreds to thousands of feet across, thousands of feet long, and tens to hundreds of feet thick. Internal spatial complexity is high, resulting from the collapse and

coalescing of numerous passages and cave-wall and cave-ceiling strata. These breccias and fractures are commonly major reservoirs in the Ellenburger Group. Hydrocarbon production ranges from as shallow as 856 ft in West Era field in Cooke County, Texas, to as deep as 25,735 ft in McComb field in Pecos County, Texas.

The Ellenburger Group is therefore considered to be an appropriate analogue to direct exploration to identify potential “coalesced, collapsed palaeocaves” in the Waulsortian Limestone of the Shannon Trough.

4.3 Evidence of Karstification

In summary of the introductory sections, karstification of the Waulsortian can be expected to have taken place (and preserved) and the evidence of which is as follows

1. Karst features in outcrop/borehole data

Anecdotal evidence and that from borehole drilling reports and core descriptions clearly states occurrences of cavities and breccias that are all related to karstification and possibly collapse.

2. Uplift and erosion post-dating deposition of Waulsortian

Post depositional uplift of carbonates may cause exposure of surfaces, making karstification more likely. Multiple episodes of uplift are recorded in the literature (Drew & Jones, 2000) and may have been instances of Waulsortian karstification

3. Marine incursions

The action of mixed marine and fresh water on carbonates makes susceptibility to karstification increase. Multiple events of marine incursion are recorded in the literature.

“The end of the Carboniferous Period, marked by earth movements and general elevation of the land, left all of Ireland above sea level in the early Permian and the succeeding eras saw a series of marine incursions from the east in the Upper Permian, Rhaetic, Liassic and Upper Cretaceous times. Each of these seems to have been more extensive than its predecessors, culminating in the Senonian transgression which may have covered all of Ireland. Cretaceous chalk at Ballydeanlea appears as matrix in a breccia of Namurian shale formed probably by collapse of a cavern in the underlying Carboniferous Limestone which mixed unconsolidated Cretaceous sediment with brecciated shale from the seafloor” (Wilson, 1981).

“Multiple episodes of prolonged subaerial exposure played a key role in porosity development and distribution in the Ellenburger Group. With each event these rocks were invaded by vadose and phreatic meteoric waters. These fresh waters modified and overprinted existing pore networks and created new porous zones. Some grain supported lithologies that contained preserved porosity at the time of uplif subaerial exposure likely functioned as freshwater aquifers during major exposure events. It appears that carbonate dissolution and cave formation were significant at and along major block boundaries within such aquifer systems” (Fritz, et al., 1993).

4. Faults as conduits of fluid flow

The presence of large faults increases the potential for a formation to be karstified as these faults are likely to be conduits of upward (and downward) fluid flow. The upward flow brings heated hydrothermal fluids that easily dissolve carbonate rocks and may exploit pre-existing fracture zones or cave systems or may even be the cause of the formation of new ones. We relate the Ellenburger to the Waulsortian in the Irish Midlands. The Ouachita Thrust causes fluid flow into the Ellenburger (Loucks, 1999). Could the Variscan front be the cause of upward (and northward) movement of fluid flow into the Waulsortian leading to deep karst formation or enhancement of pre-existing palaeokarsts? Some mention of the implications of the Variscan front on dolomitizing fluid flow has been made in (Hitzman, et al., 1998).

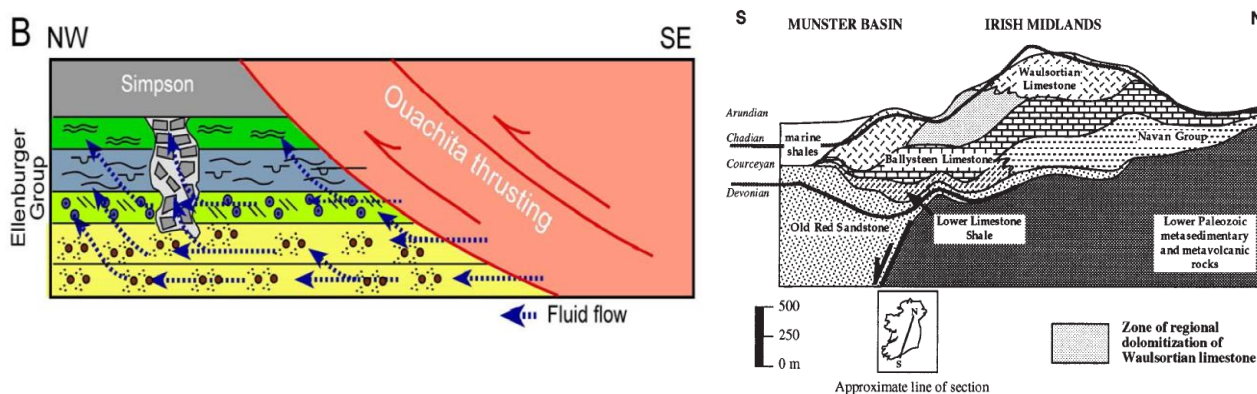


Figure 6. (left) Illustration of the Ouachita thrusting and its influence on fluid flow in the Ellenburger formation, W. Texas (Loucks, 1999). (right) Hercinian orogeny and its hypothesised influence on the dolomitization of the Waulsortian in the Irish Midlands (Hitzman, et al., 1998).

4.4 GIS Database

A single Project GIS database was created to ensure that all the available information could be used to develop a good spatial understanding of the region.

- Relevant publicly available shapefiles were imported into the database. These include *Bedrock Geology, Strat/Struct lines, Groundwater(wells), Aquifer, Tracer, SEAI files etc.*
- New shapefiles were created from available data including:
 - “Points” for ‘Karst features from (Drew & Jones, 2000)’
 - “Points” for relevant borehole including information available on the EMD website: (<http://spatial.dcenr.gov.ie/>) that were at depths >500m and in the region of interest.
 - Limestone layers (including dolomitized zone as in (Hitzman, et al., 1998)) from maps in published work.
 - Seismic Coverage in the possession of iCrag
 - Regional Geological trend from literature
- GIS data from Hannan Metals Seismic Dataset
- Georeferenced overlays of all the maps used to create new shape files

This dataset was maintained in QGIS and was updated several times as the project progressed.

4.5 Seismic Analysis

This project aimed to use a common Oil & Gas exploration technique - Seismic Analysis, in order to identify deep karst features. A seismic analysis undertaking is best carried out in the following steps (AAPG Wiki, 2016):

Step one: interpretation plan

- What are the objectives?
The primary objective was to identify karst features within the Waulsortian at depths that would be appropriate for geothermal resource exploration (and CO₂ Storage)
- What are the regional tectonic, structural, and depositional trends?

As discussed in previous sections, a thorough literature review was carried out. Major regional tectonic structural and depositional trends were understood, with a focus on their implications on the Waulsortian. All the available data was imported into the Project GIS Database. All available geothermal modelled/observed data points (wells, boreholes etc.) as well as SEAI maps were included to help steer the seismic investigation.

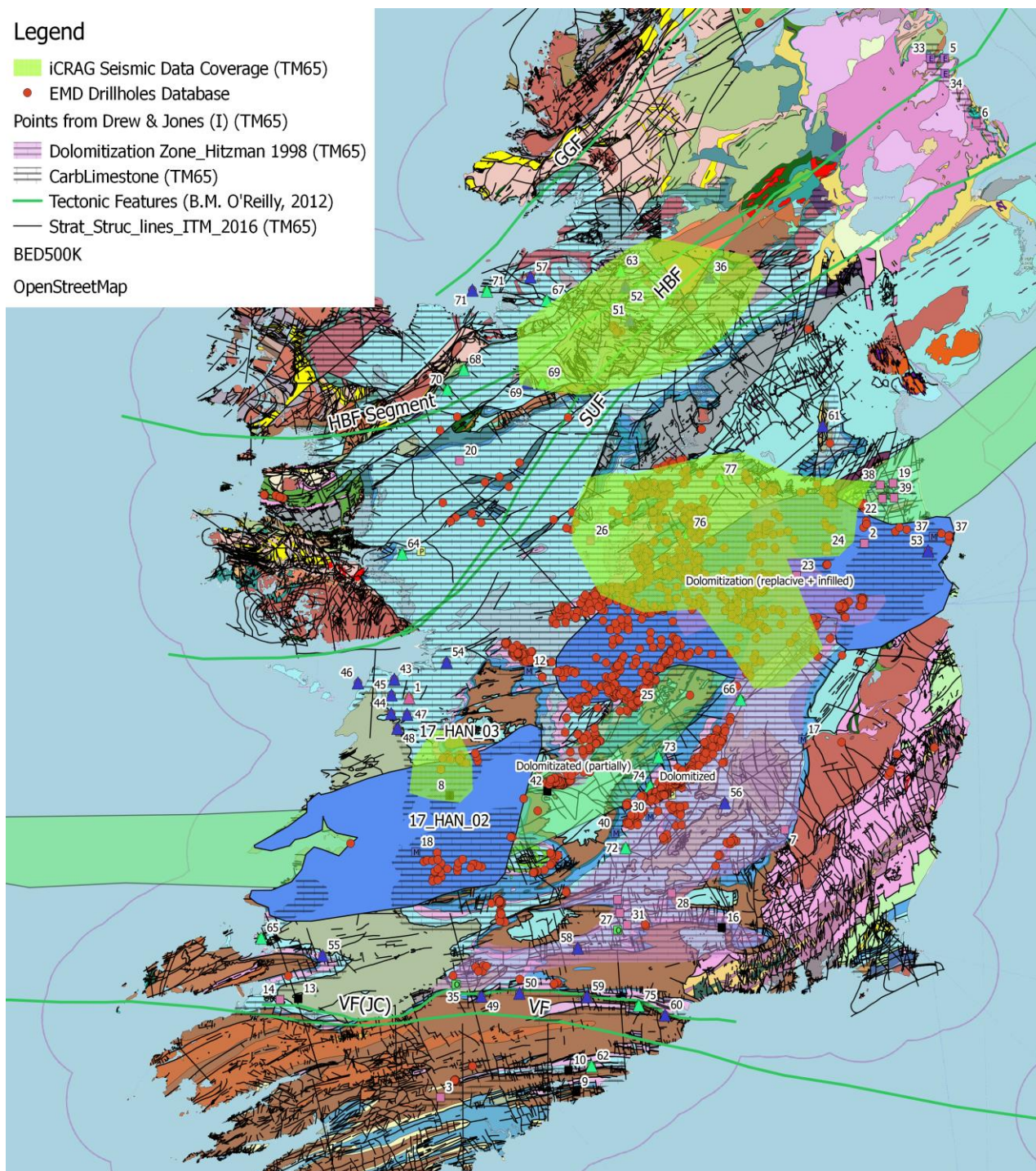


Figure 7. Compilation of data into a single GIS Database.

- What seismic patterns should one be looking for?
In the Ellenburger Group, the coalesced collapsed palaeocaves were identified (interpreted) on the seismic data at locations where 'missing reflections' coincided with locations above which supra-stratal deformation (in the form of sag structures, cylindrical faults etc.) was observed (Figure 8). In the Ordovician Palaeokarst strata, Central Tabei uplift, Tarim Basin, Western China, seismic features in the overlying strata such as onlap, bright spots, sag, faults etc were used to identify deep-karst (Figure 9)

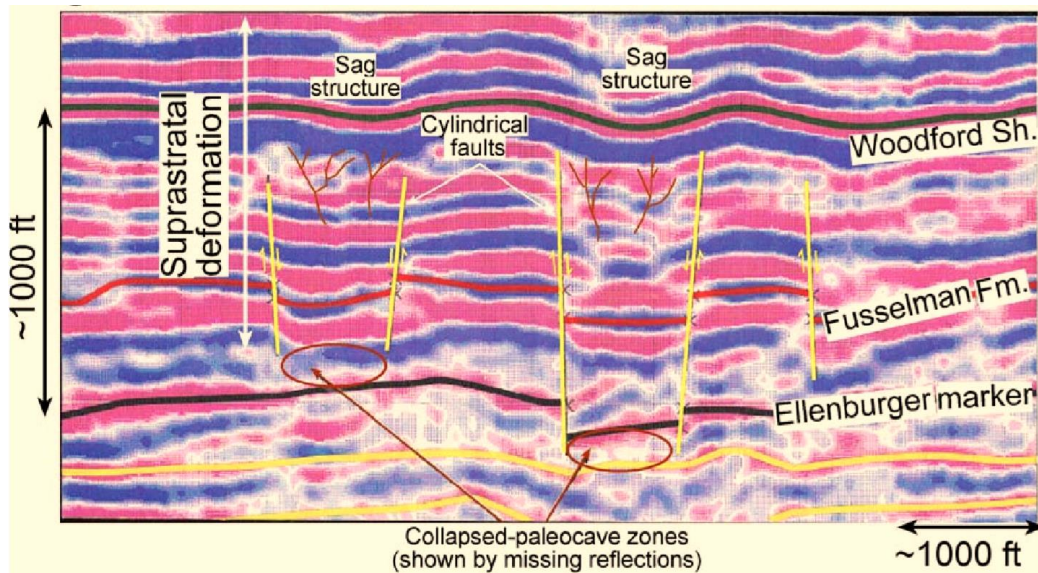


Figure 8. 3-D Seismic example over an Ellenburger palaeocave system, West Texas (Loucks, 1999)

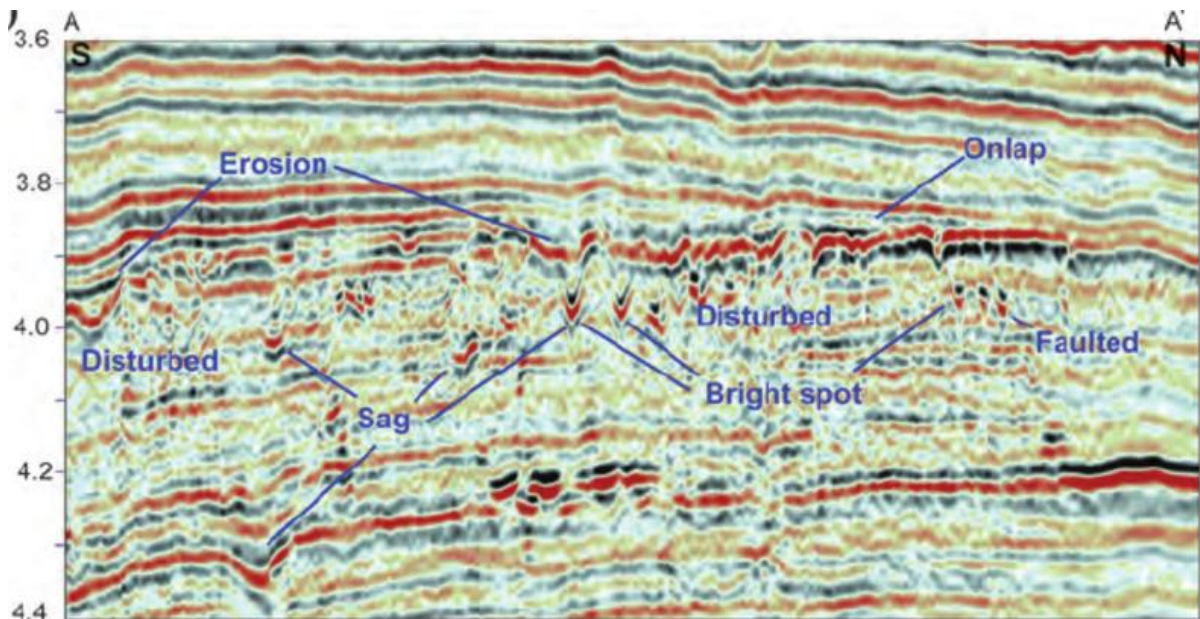
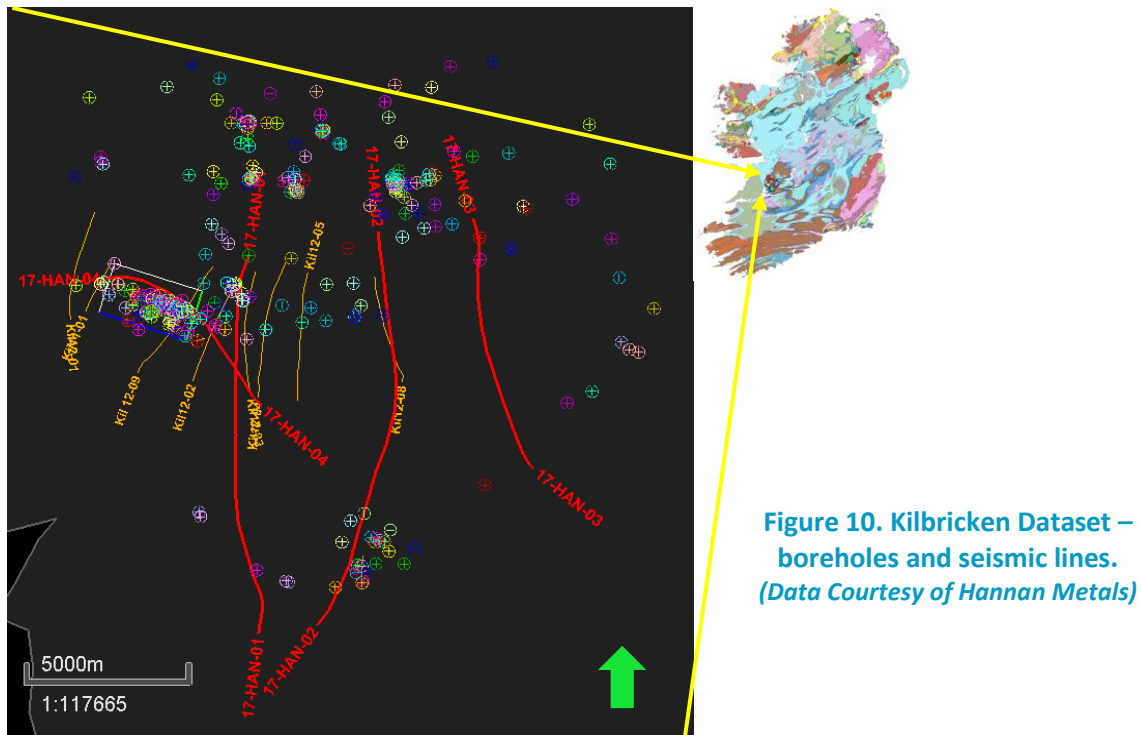


Figure 9. Seismic dip section of Ordovician Palaeokarst strata, Central Tabei uplift, Tarim Basin, Western China (Zeng, et al., 2011)



Step two: interpretation plan

- Building and merging datasets
With interpretation plan in place, all the available data was compiled into a single Petrel Project file. The data was kindly provided for this project by Hannan Metals (and was accessed in iCrag – UCD). The project dataset consisted of four 2017 2D Seismic Lines, seven 2012 2D Seismic Lines and one 2012 3D Seismic Dataset (Figure 10). The project also included Hannan's Kilbricken Borehole database - locations and trajectory of 458 Boreholes, Logs of Alteration, Assays, Breccia, Drill Collar, Lithology & Mineralization for most. A key step in the seismic interpretation exercise is converting Seismic Dataset i.e. in the time domain to depth domain. This step was carried using the only provided VSP Log for **1 Well** (125m from 17-Han-04). This TDR was then used to convert all data from time domain to depth domain. The 2012 2D seismic lines and 3D cube were very poor quality and resolution and hence only the four 2017 2D seismic lines were analysed.

Step three: Interpret!

- The four 2017 2D Seismic Lines were interpreted with focus mainly on the Waulsortian Top and base. The seismic reflection signature of the Waulsortian Top and Base was inferred from a seismic well-tie from a publicly available presentation by Hannan Metals. A more in-depth analysis was doing of the Waulsortian interval with focus on location showing sag features in the strata overlying. The seismic lines had poor reflector continuity and lack of identifiable bedding. There were patchy high amplitude reflectors that could be due to mineralization. Fault planes were not easy pick out.
- The borehole data included litho-logs and other features identified during the drilling and core-logging exercise. Features included zones of brecciation and cavities. These were projected on the seismic line for wells within reasonable distance (~0-350m).

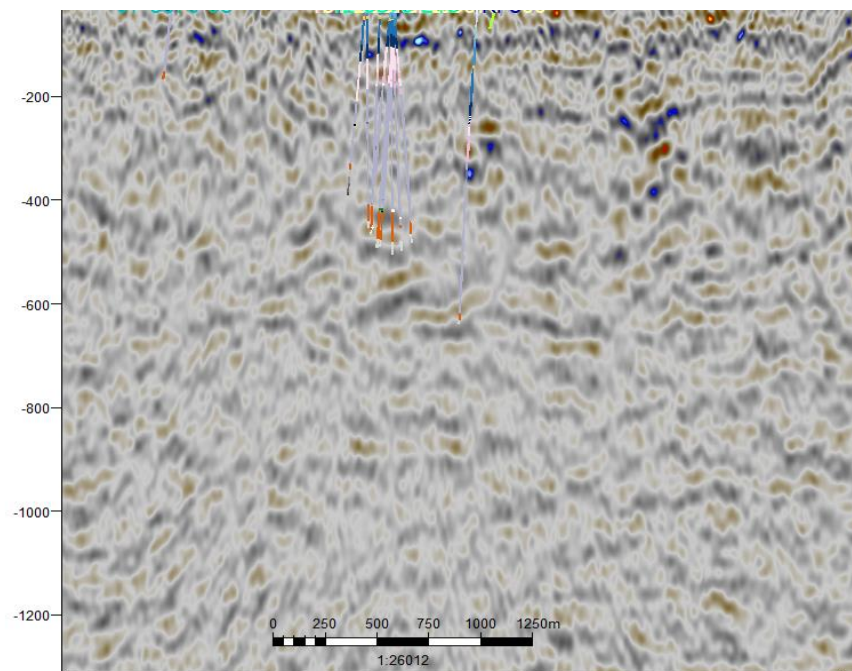


Figure 11. Kilbricken Dataset – example of 2012 2D seismic line (*Data Courtesy of Hannan Metals*)

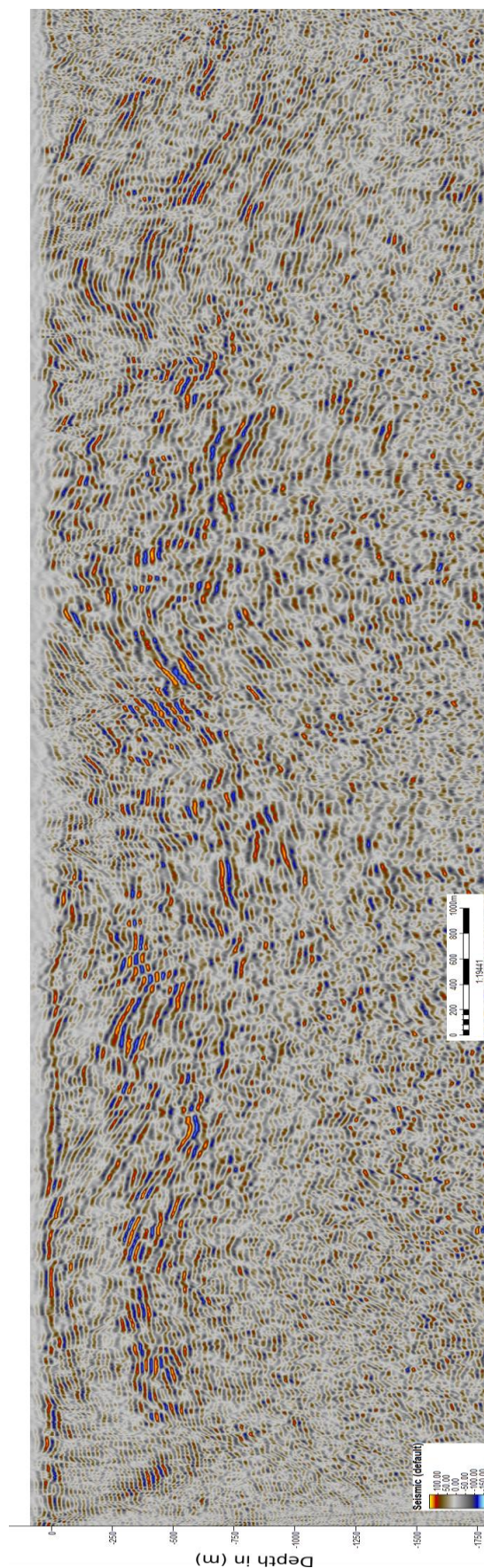


Figure 12. Kilbricken Dataset – example of 2017 2D seismic line (Data Courtesy of Hannan Metals)

Results of Seismic Analysis

The interpretation carried out as part of this project was compared to that carried out by iCRAG Researchers as well as Hannan Metals. There was a significant difference in interpretations as one would expect given the quality of the data, but interpretation of key elements such as major faults was similar.

The base of the Waulsortian was interpreted to be as deep as 900m in one of the 2017 2D lines. With the primary objective in mind, the analysis was focused only on regions where the Base-Waulsortian was deepest. A general deepening of the Waulsortian was observed towards the south, and this was supported by regional geology. One of the major faults in the south (dipping north) (blue fault in Figure 13), in the Kilmurry area, had a displacement of greater than 200m, with the depth of the Base of the Waulsortian on the hanging wall at ~900m. Large faults are known to be conduits for upwards movement of fluids from deeper sources.

Interestingly, sag patterns were observed in the high amplitude reflectors between 400m-700m above the deepest point of the Waulsortian (against the fault). The reflectivity was observed to reduce with depth, however, polygonal faults in the overlying strata appeared to be radiating from a focal point (location).

In addition, a well located 200m away, projected on the seismic line, that appeared to intersect many of these sag features, was recorded to have several zones of breccia and cavities at depth. The deepest cavity recorded was 0.35m at 710m depth.

We interpret this to be the location of a 'Coalesced Collapsed Palaeocave' at the base of the Waulsortian cause a collapse of overlying strata, thus forming sag features and polygonal faults.

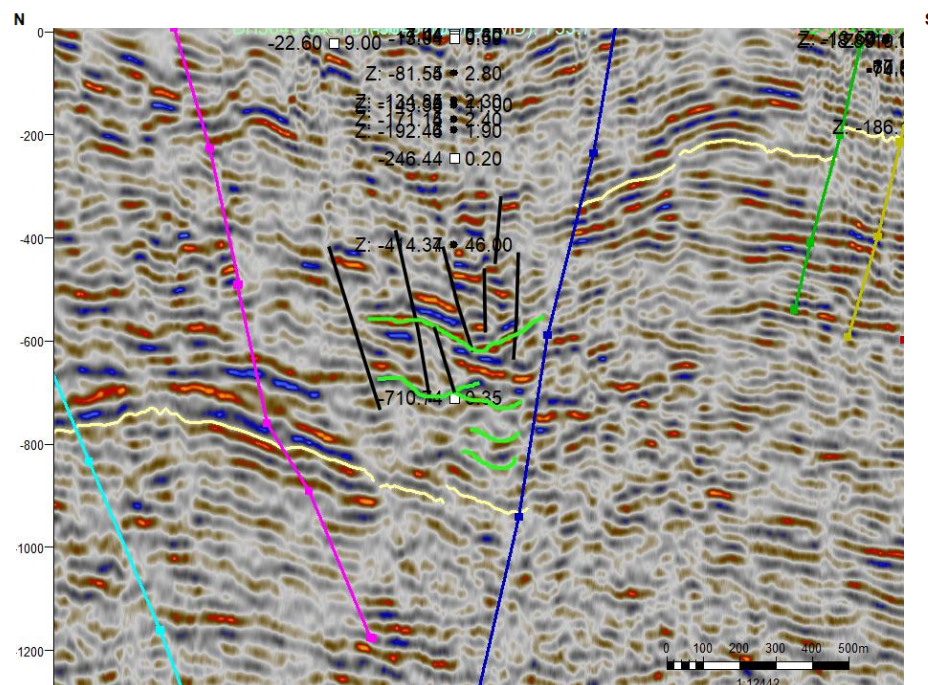


Figure 13. Focused seismic section of a 2017 2D line with projections of cavity/brecciation locations and project interpretations of sag features and faults (Data Courtesy of Hannan Metals)

5.0 Drilling Proposal

The results of the seismic analysis, accompanied by evidence in the literature and anecdotal evidence from experts would lead one to suspect the presence of a 'Coalesced Collapsed Palaeocave' in the Kilmurry region with substantial confidence.

We thus propose drilling the Kilmurry Prospect

- Collapsed Paleocave – at **~900m depth**
- Potential for temperatures of **between 30°C to 40°C** (*SEAI Modelled Temperatures at Depth*)
- As in Ellenburger 'Ramp Carbonates' play type, one would expect porosities from 2 to 14% with moderate permeabilities

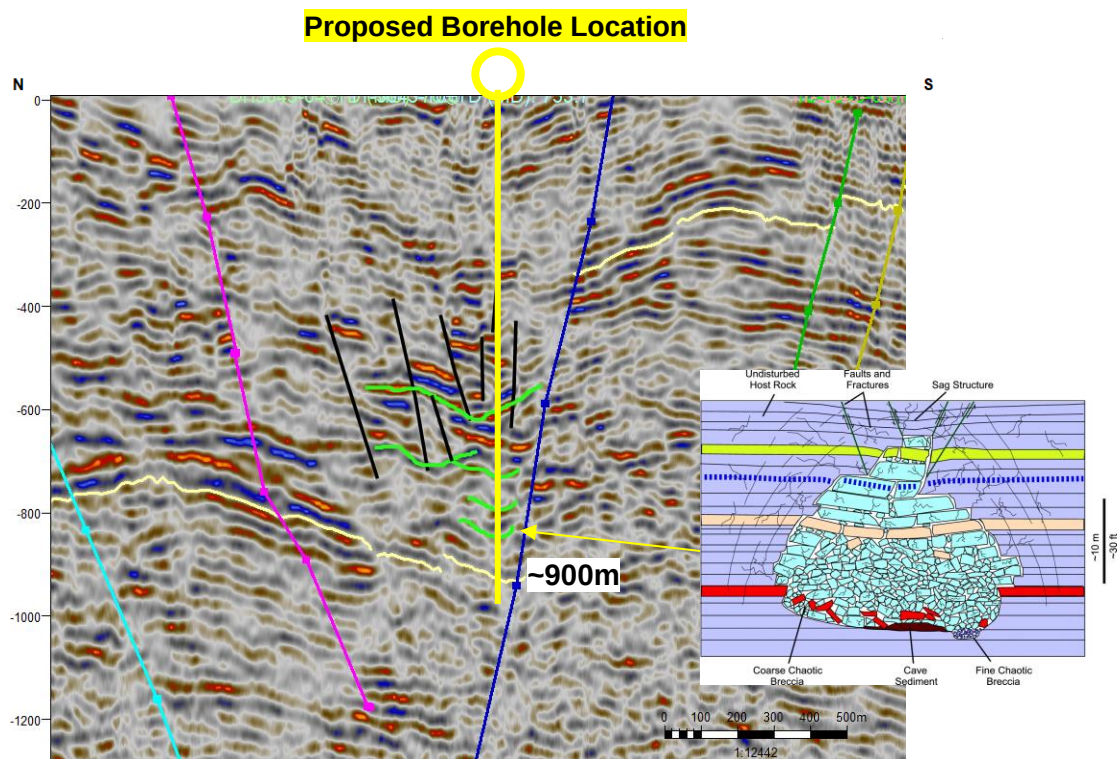


Figure 14. Proposed location for borehole to drill Kilmurry Prospect - Coalesced Collapsed Palaeocave with target at ~900m depth. Comparison with Ellenburger conceptual model. (Data Courtesy of Hannan Metals)

6.0 Recommendations

As an outcome of this study, a few recommendations are made here below, that would greatly benefit the Geothermal Exploration Industry and Ireland's goals of exploiting geothermal energy for heating and electricity by 2020 and 2040. Although, the recommendations are specific to the study area and the project findings, the overall need for investment and data-acquisition in the geothermal industry is nationwide.

Recommendations

- I. Drill the proposed "Kilmurry Prospect" to verify seismic interpretation of karst indicators.
- II. Acquire Petrophysical logs while drilling to better characterise the stratigraphy and create a more constrained manual for identifying karst indicators on seismic.
- III. Seismic data, (preferably 3D Seismic) further south where the Waulsortian is predicted to be deeper.

Drilling of a deep borehole along with acquisition of a comprehensive suite of petrophysical logs will help explorers better constrain seismic interpretations as well as potential models of karst reservoirs. Temperature data can further enhance one's ability to constrain prospective resources estimates as current reliance is on temperature models that are based on sparse distribution of data-points.

Transfer of knowledge from the Petroleum Exploration industry, in the use of seismic data was the core element of this study. Seismic data helps better understand and quantify resources and can be used advantageously in the geothermal industry. In addition, the mineral exploration industry in Ireland is, only recently, seeing the benefits of using seismic data. And it appears to be an opportune moment for the geothermal industry to piggy back this strategy.

In terms of this study, the Waulsortian is predicted to be much deeper south of the Kilbricken seismic coverage area. Reiterating that 'depth to Waulsortian/target' is key, locating the Waulsortian at depths greater than 1000m would imply more gainful geothermal resources (potentially from deep karst or coalesced collapsed palaeocaves)

7.0 Conclusions

As a result of this preliminary research project, a number of conclusions can be made.

- The anecdotal evidence of cavities, brecciated zones, missed sections at depth from mineral exploration drilling in Ireland is confirmed from borehole records.
- Review of Palaeozoic geology in Europe (N. Belgium) and the US (W. Texas) confirms the existence of porous and permeable carbonate reservoirs preserved at depth associated with karstification.
- New seismic data acquired from mineral exploration onshore Ireland displays features indicative of coalesced collapsed palaeocave systems at depth as observed in the Ellenburger Group, W. Texas.
- An opportunity exists to collaborate with the mineral exploration sector to drill a deep exploratory research borehole to test the 'coalesced collapsed palaeocave' exploration model.

8.0 Bibliography

- Allan, J. R. & Wiggins, W. D., 1991. *Dolomite Geochemistry Manual*, s.l.: Chevron.
- Anderson, H., Walsh, J. & Cooper, M., 2016. Faults, intrusions and flood basalts: the Cenozoic structure of the north of Ireland. In: M. Young, ed. *Unearthed: impacts of the Tellus surveys of the north of Ireland..* Dublin: Royal Irish Academy, pp. 179-189.
- Anon., 2016. AAPG Wiki. [Online] Available at: http://wiki.aapg.org/Seismic_interpretation [Accessed 05 11 2018].
- Anon., 2016. An investigation of thermal springs in Ireland: their provenance, pathways and geothermal potential. *Irish Groundwater Newsletter*, Issue 54, pp. 35-38.
- Atkins, 2013. *Deep Geothermal Review Study*, Dublin: Department of Energy & Climate Change (DECC).
- Awawdeh, R. E. et al., 2008. *3-D Seismic Evidence of Tertiary - Cretaceous Karsts & Collapse Disturbances from Offshore Oil Field in Abu Dhabi and Outcrop Analogs from Jebel Hafit, United Arab Emirates*. Abu Dhabi, Society of Petroleum Engineers.
- B. M. O'Reilly, F. H. a. P. W. R., 2012. The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: implications for the origins of the 'Newer Granites'. *Journal of the Geological Society*, 3 September, Volume 169, pp. 561-573.
- Blake, S. et al., 2016b. Understanding hydrothermal circulation patterns at a low-enthalpy thermal spring. *Journal of Applied Geophysics*, Volume 132, pp. 1-16.
- Blake, S. et al., 2016. *Characterising the hydrothermal circulation patterns beneath thermal springs in the limestones of the Carboniferous Dublin Basin, Ireland: a geophysical and geochemical approach..* s.l., EGU General Assembly 2016.
- Blake, S. et al., 2015. *A Multi-Disciplinary Investigation of Irish Warm Springs and Their Potential for Geothermal Energy Provision*. Melbourne, Proceedings World Geothermal Congress 2015.
- Bonijoly, D. et al., 2003. *Feasibility of CO₂ storage in geothermal reservoirs example of the Paris Basin - France*, s.l.: BGRM-CFG-ANTEA contribution to the GESTCO Project.
- Chalaturnyk, R., 2012. Risk Assessment. In: B. Hitchen, ed. *Best practices for validating CO₂ geological storage: observations and guidance from the IEAGHG Weyburn Midale CO₂ monitoring and storage project*. s.l.: Geoscience Publishing.
- Coxon, P., 2005. The late Tertiary landscapes of western Ireland. *Irish Geography*, 38(2), pp. 111-127.
- CSA Group, 2008. *Assessment of the Potential for Geological Storage of Carbon Dioxide for the Island of Ireland*. Dublin: Sustainable Energy Ireland.
- DEWAIDE, L. et al., 2014. Karstification in dolomitized Waulsortian mudmounds (Belgium). *GEOLOGICA BELGICA*, 17(1), pp. 43-51.
- Dolan, M. et al., 2018. *Investigation of buried limestone valleys between Lough Corrib and Galway City*. Galway, ResearchGate.
- Drew, D. P. & Jones, G. L., 2000. Post-Carboniferous pre-Quaternary karstification in Ireland. *Proceedings of the Geologists' Association*, 111(4), pp. 345-353.
- Eide, C. H. et al., 2018. Seismic interpretation of sill complexes in sedimentary basins: implications for the sub-sill imaging problem. *Journal of the Geological Society*, Volume 175, pp. 193-209.

- Fritschle, T. et al., 2018. Multiple intrusive phases in the Leinster Batholith, Ireland: geochronology, isotope geochemistry and constraints on the deformation history. *Journal of the Geological Society*, Volume 175, pp. 229-246.
- Fritz, R., Wilson, J. & Yurewicz, D., 1993. *Paleokarst Related Hydrocarbon Reservoirs*, New Orleans: SEPM Core Workshop No 18.
- Galdenzi, S. & Menichetti, M., 2016. *ACTIVE HYPOGENIC KARST IN ITALY*. s.l., DeepKarst 2016.
- Gregg, J. M. et al., 2001. Dolomitization of the Waulsortian Limestone (Lower Carboniferous) in the Irish Midlands. *Sedimentology*, Volume 48, pp. 745-766.
- Günay, G. & Şimşek, Ş., 2001. *KARST HYDROGEOLOGY IN HYDROTHERMAL SYSTEMS*. Ankara, Present State and Future Trends of Karst Studies; Günay, Ford, Johnson&Johnson, 2001-UNESCO.
- Higgs, K. T. & Jones, G. L., 2000. Palynological evidence for Mesozoic karst at Piltown, Co. Kilkenny. *Proceedings of the Geologists' Association*, Volume 111, pp. 355-362.
- Hitzman, M. W., 1995. Geological setting of the Irish Zn-Pb-(Ba-Ag) orefield. In: *Irish Carbonate Hosted Zn-Pb Deposits*. s.l.:Society of Economic Geologists.
- Hitzman, M. W., Allan, J. R. & Beaty, D. W., 1998. Regional dolomitization of the Waulsortian limestone in southeastern Ireland: Evidence of large-scale fluid flow driven by the Hercynian orogeny. *Geology*, June, 26(6), pp. 547-550.
- Hurter, S. & Schellschmidt, R., 2003. Atlas of geothermal resources in Europe. *Geothermics*, Volume 32, pp. 779-787.
- Johnson, A. W. et al., 2009. Regional studies of dolomites and their included fluids: recognizing multiple chemically distinct fluids during the complex diagenetic history of Lower Carboniferous (Mississippian) rock of the Irish Zn-Pb ore field. *Miner Petrol*, 20 January, Volume 96, pp. 1-18.
- Jones, G. L. & Fitzsimons, J., 1992. A pure dolomite deposit northeast of Cahir, Co. Tipperary. In: A. Bowden, G. Earls, P. O'Connor & J. F. Pyne, eds. *The Irish Minerals Industry 1980-1990*. Dublin: Ir. Assoc. Econ. Geol, pp. 327-334.
- Kelly, J. G., Fogg, T. & Enlander, I., 1996. Holocene and Tertiary karstification in the Ulster White Limestone Formation (Cretaceous) of the Garron area, County Antrim, Northern Ireland. *Cave and Karst Science*, 23(3), pp. 93-100.
- Klimchouk, A. B., Ford, D. C., Palmer, A. N. & Drebrodt, W., 2000. Part 3. In: *Speleogenesis: Evolution of Karst Aquifers*. s.l.:National Speleological Society, pp. 44-64.
- Laenen, B., Van Tongeren, P., Dreesen, R. & Dusaar, M., 2004. Carbon dioxide sequestration in the Campine Basin and the adjacent Roer Valley Graben (North Belgium): An inventory. *Geological Society, London, Special Publications*, Volume 233, pp. 193-210.
- Laskow, M. G. M. G. I. G. H. F. A., 2011. Deep confined karst detection, analysis and palaeo-hydrology reconstruction at a basin-wide scale using new geophysical interpretation of borehole logs. *Journal of Hydrology*, Volume 406, pp. 158-169.
- Ledsaak, K., 2016. *Geo-modelling of paleokarst reservoirs - from cave-survey to geocellular paleokarst model*. Bergen: (unpub - Master's Thesis).
- Lees, A. & Miller, J., 1995. Waulsortian banks. In: *Carbonate mud-mounds: their origin and evolution..* Oxford: Special Publication of the International Association of Sedimentologists, pp. 191-271.
- Loucks, R., 1999. Paleocave Carbonate Reservoirs: Origins, Burial-Depth Modifications, Spatial complexity and Reservoir Implications. *AAPG Bulletin*, 83(11), pp. 1795-1834.

- Loucks, R., 2003. *REVIEW OF THE LOWER ORDOVICIAN ELLENBURGER GROUP OF THE PERMIAN BASIN, WEST TEXAS*. s.l., s.n.
- McCormack, T. et al., 2017. Characterisation of karst hydrogeology in Western Ireland using geophysical and hydraulic modelling techniques. *Journal of Hydrology: Regional Studies*, Volume 10, pp. 1-17.
- Murray, J. & Henry, T., 2018. *Wausortian Limestone: Geology and Hydrogeology*. Tullamore, s.n.
- Nagy, Z. R. et al., 2005. Lower Carboniferous peritidal carbonates and associated evaporites adjacent to the Leinster Massif, southeast Irish Midlands. *Geological Journal*, Volume 40, pp. 173-192.
- Palmer, A. N., 2007. Influence of geology on cave patterns. In: *Cave Geology*. s.l.:Cave Books, pp. 232-270.
- Reed, C. P. & Wallace, M. W., 2000. Diagenetic evidence for an epigenetic origin of Courtbrown Zn-Pb deposit, Ireland. *Mineralium Deposita*, Volume 36, pp. 428-441.
- Saller, A. H., Budd, D. A. & Harris, P. M., 1994. Unconformities and Porosity Development in Carbonate Strata: Ideas from a Hedberg Conference. *AAPG Bulletin*, 78(6), pp. 857-872.
- Simms, M. J., 2000. The sub-basaltic surface in northeast Ireland and its significance for interpreting the Tertiary history of the region. *Proceedings of the Geologists' Association*, Volume 111, pp. 321-336.
- Somerville, I. D. & Jones, G. L., 1985. The Courcayan stratigraphy of the Pallaskenry Borehole, County Limerick, Ireland. *Geological Journal*, Volume 20, pp. 377-400.
- Somerville, I. D., Strogon, P. & Jones, G. L., 1992. Biostratigraphy of Dinantian limestones and associated volcanic rocks in the Limerick Syncline. *Geological Journal*, Volume 27, pp. 201-220.
- Stolfova, K. & Shannon, P. M., 2009. Permo-Triassic development from Ireland to Norway: basin architecture and regional controls. *GEOLOGICAL JOURNAL*, Volume 44, pp. 652-676.
- Strogon, P., 1988. The Carboniferous Lithostratigraphy of Southeast County Limerick, Ireland, and the Origin of the Shannon Trough. *Geological Journal*, Volume 23, pp. 121-137.
- Strogon, P., Jones, G. L. & Somerville, I. D., 1990. Stratigraphy and sedimentology of lower carboniferous (Dinantian) boreholes from West Co. Meath, Ireland. *Geological Journal*, Volume 25, pp. 103-137.
- Strogon, P. et al., 1996. Controls on ramp, platform and basinal sedimentation in the Dinantian of the Dublin Basin and Shannon Trough, Ireland. *Geological Society London Special Publications*, January, 107(1), pp. 263-279.
- Wilson, H. E., 1981. Permian and Mesozoic. In: C. Holland, ed. *A Geology of Ireland*. Edinburgh: Scottish Academic Press, pp. 201-211.
- Zeng, H. et al., 2011. Characterizing seismic bright spots in deeply buried, Ordovician Paleokarst strata, Central Tabei uplift, Tarim Basin, Western China. *Geophysics*, 76(4).
- Zhu, H., Zhu, X. & Chen, H., 2017. Seismic Characterization of Hypogenic Karst Systems Associated with Deep Hydrothermal Fluids in the Middle-Lower Ordovician Yingshan Formation of the Shunnan Area, Tarim Basin, NW China. *Geofluids*, p. 13.

APPENDIX 01 KEY BOREHOLES

We investigated the borehole log reports in the public domain (<http://spatial.dcenr.gov.ie/>) and identified boreholes that show potential evidence for karstification in the Waulsortian Reef intervals in the area around the Hannan Metals Seismic Coverage. Features like cavities, breccias, 'broken ground' etc. were considered as reasonable evidence for karstification, as well as indicators for good poro-perm retention even at depths of up to 700m. Most cavities were <1m, however, their mere presence leads one to speculate the presence of cavities of valuable size ranges. See below a list of some of the important boreholes with mentioned features at depth.

PL No	Borehole	Waulsortian	Cavity Features		Brecciated Zones		Broken	
		Interval (m)	Interval (m)	Comments	Interval (m)	Comments	Interval (m)	Comments
3642	09-3642-01	9 – 449.5 (EOH) Hole Abandoned	22.65 - 22.95	No recovery				
			27.30 - 28.50	Cavity, no recovery				
			93.40 - 94.45	Cavity, no recovery				
			331.6 - 342.9	No recovery. Drill reduced to BQ to continue.				
							437.4 – 440.0	Bleached and altered waul. Broken and weathered. Pos including small cavities.
		440.0- 442.0	Cavity, no recovery					
		443.7 - 449.5	Cavity, no recovery. No water pressure. Large cavity, unlikely to be able to cement.					

				Hole abandoned.		
3679	09-3679-08	262.55 – 462.6			264.15 – 264.45	Brecciated. Clast to matrix supported locally. Clasts are vfgr to 3-5cm, angular and unspherical. Matrix is dark grey vfgr material, probably BMB related dolomite, with vfgr lithoclasts.
					264.45 – 301.0	Waul as above with sections of breccia similar to those in the supra-waulsortian.
			367.1 - 368.1	Cavity with minor rubble recovery. Rock on roof and floor is weathered suggesting fluid flow		
			368.5 – 368.8	Joint or cavity with brown sandy fill.		
3643	11-3643-10	6 - >753.7 (EOH)	6.0 – 44.7	Cavity.		
			48.1 – 48.4	Cavity.		
			53.7 – 54.2	Cavity.		
					122.2 – 126.7	Black Matrix Breccia from 122.2-126.7m, moderate to well developed, sub-angular to sub-rounded clasts, clasts

						of varying size and lithologies. Clasts in a finer grained matrix. Slickensides parallel to bedding at 120.3m and 121.4m.				
			169.8 – 170.1	Dark grey and very fine-grained cavity fill at 169.8-170.1m. This cavity fill is bound by calcite veins at either end, 1cm calcite vein at 169.8m and 3cm thick calcite vein at 170.1m.						
									190.3 - 191.0	Broken ground
					192.3 - 195.2	Black Matrix Breccia				
					199.3 – 200.3	Breccia at 199.3-199.5m, 199.6-199.65m and 200.2-200.3				
			202.7-203.2	Fine grained, mud, dark grey cavity infill						
					211.6 – 212.8	Breccia at 211.6-211.7m with clasts ranging in size from 2mm-25mm in a finer grained black matrix. Waulsortian Reef at 211.7-212.0m. Breccia at 212 212.8m with clasts 2mm-35mm in a finer grained black matrix.				

				213.7 – 228.4	BMB at 213.7-214.3m with clasts size ranging from 2mm-50mm. BMB at 213.7-214.3m, 226.4-227m and 227.6-228.4m. BMB at 227.6-228.4m.	
				233.1 – 237.1	Waulsortian Reef with Black Matrix Breccia, clasts sizes range from 1mm-60mm in a finer grained medium grey matrix. BMB at 233.1-234.5m and 236.4-237.1m.	
				287.1 – 287.3	Cavity.	
					300.8 - 301.0	Fe-Ox in broken surfaces
					327.3 - 327.7	Broken ground
					389.6 – 390.1	Broken ground at 388.6-389.3m and 389.6-390.1m
					454.1 – 487.3	Broken ground at 454.1-454.2m, 459.2-460.3m, 460.8-461.4m, 462.95-463.15m, 465.3-466.0m, 466.7-467.8m, 469.5-471.0m, 472.0m, 485.7- 485.9m and 487.0-487.3m.
					496.3-496.5	Broken ground

					502.3-503	Broken ground
					525.9 – 548.7	Broken ground at 525.9-526.1m, 531-531.3m and 534-535m, haematitic in parts. Clay along fractures at 538-539.3m. Broken ground with Fe-Ox at 539.6-540.5m. Broken ground at 541.7-542.4m, 545.5-546.1m and 547.8- 548.7m.
					549.5 – 581.9	Broken ground at 549.5-549.8m, 553.6-554.3m, 555.4-556m, 556.8-558.4m, 559.5-560.5m, 561.1-563.4m, 568.3-568.5, 569.3-569.6m, 572.3-572.6m, 573.7-574.2m, 581-581.4m and 581.8- 581.9m.
					594.0 – 646.9	Broken ground at 594.0-594.6m, 596.3-596.7m, 598.9-599m, 606.6-606.8m, 611.8-611.9m and 613.0-613.1m. Fractured at 603.0-604.0m and 608.0-608.4m. Fe-Ox staining on fractured surfaces from 612.1-612.5m. Broken ground at 638.7-639.3m, 641.4-

						642.1m, 646.6-646.9m
					654.3 – 682.7	Broken ground at 654.3-654.5m, 660.6-660.7m, 665.0-665.1m, 668.6-669.1m and 682.4-682.7m.
					721.7-722.2	Broken ground
			751.4 - 751.8	Cavity.		

EUROPEAN OFFICES

United Kingdom

AYLESBURY

T: +44 (0)1844 337380

BELFAST

T: +44 (0)28 9073 2493

BRADFORD-ON-AVON

T: +44 (0)1225 309400

BRISTOL

T: +44 (0)117 906 4280

CAMBRIDGE

T: + 44 (0)1223 813805

CARDIFF

T: +44 (0)29 2049 1010

CHELMSFORD

T: +44 (0)1245 392170

EDINBURGH

T: +44 (0)131 335 6830

EXETER

T: + 44 (0)1392 490152

GLASGOW

T: +44 (0)141 353 5037

GUILDFORD

T: +44 (0)1483 889800

LEEDS

T: +44 (0)113 258 0650

LONDON

T: +44 (0)203 691 5810

MAIDSTONE

T: +44 (0)1622 609242

MANCHESTER

T: +44 (0)161 872 7564

NEWCASTLE UPON TYNE

T: +44 (0)191 261 1966

NOTTINGHAM

T: +44 (0)115 964 7280

SHEFFIELD

T: +44 (0)114 245 5153

SHREWSBURY

T: +44 (0)1743 23 9250

STAFFORD

T: +44 (0)1785 241755

STIRLING

T: +44 (0)1786 239900

WORCESTER

T: +44 (0)1905 751310

Ireland

DUBLIN

T: + 353 (0)1 296 4667

France

GRENOBLE

T: +33 (0)4 76 70 93 41